Accessing Polarized Sea Quark Flavor Asymmetry through Semi-Inclusive DIS at JLab-12GeV (and the Future EIC)

(Based on JLab Hall A Collaboration Proposal PR12-14-008)


Semi-Inclusive double-spin asymmetry $A_{LL}^h$ in $^3\overline{H}e(e, e'h) \ h = \pi^+, \pi^-, K^+, K^- (\pi^0)$

$A_{LL,n}^h \propto A_{1n}^h = \Delta\sigma_n^h/\sigma_n^h$

- Flavor tagging in SIDIS provides access to $\Delta q$.
- Existing SIDIS data on proton and deuteron lacks precision to constrain d-quarks, neutron ($^3$He) $A_{1n}^h$ are most sensitive to $\Delta d, \Delta \overline{d}$

**This JLab proposal:** precision $A_{1n}^h$ and multiplicity data on a dense grid of $(x,Q^2,z)$:
- Strong constraints on $\Delta q$ through NLO QCD global fits.
- Leading-Order “purity”-method $\Delta q$ extraction, as in HERMES and COMPASS.
- Self-consistency cross-checks to set limits on interpretation systematics.
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A JLab Hall A Collaboration Proposal, with SBS Collaboration’s endorsement

**Collaboration carries extensive Hall A operation experiences, heavily involved in experiments such as:**

- BigBite, Super-BigBite (SBS), GEp, GEn, Transversity, SoLID...
- with a polarized $^3$He target.
- SIDIS spin asymmetry measurements.
Nucleon Spin Flavor Decomposition

- Inclusive DIS access only $q_f + \bar{q}_f$:

$$g_1(x, Q^2) = \sum_{f=u,d,s} e_f^2 \left( \Delta q_f + \Delta \bar{q}_f \right)(x, Q^2)$$

$$\Delta u + \Delta \bar{u}, \Delta d + \Delta \bar{d}$$

- Inclusive DIS access gluon via $Q^2$ evolution, at NLO:

$$g_1 = \sum_{f=u,d,s} e_f^2 C_q \otimes (\Delta q_f + \Delta \bar{q}_f) + \left( \sum_f e_f^2 \right) \alpha_s C_g \otimes \Delta G$$

we wish to determine valence quarks’ polarization:

$$\Delta u_v = \Delta u - \Delta \bar{u}, \quad \Delta d_v = \Delta d - \Delta \bar{d}$$

and determine if sea quarks carry any polarization:

$$\Delta \bar{u} \neq 0, \Delta \bar{d} \neq 0, \Delta \bar{u} - \Delta \bar{d} \neq 0$$
Quark Flavor Tagging through SIDIS

Detect the leading hadron from the current fragmentation and measure double-spin asymmetry: $A_1^h = \Delta \sigma^h / \sigma^h$.

Leading order naive $x$-$z$ separation:

$$\Delta \sigma^h = \sum_{f=q,\bar{q}} e_f^2 \Delta q_f(x) D_f^h(z)$$

Reaction on a “free quark”: highest possible $Q^2$, $W$, $p_\pi$ and $W'$.

HERMES calculated “purity” from a LUND based Monte Carlo:

$$A_1^h = \sum_a \left( \frac{e_a^2 q_a(x) D_a^h(z)}{\sum_b e_b^2 q_b(x) D_b^h(z)} \right) \frac{\Delta q_a(x)}{q_a(x)}$$

Fragmentation “tags” flavor and charge of struck quark.
HERMES-2004 and COMPASS-2010 Leading-Order $\Delta q$ extraction

Large uncertainties on $\Delta d$

sea quarks un-polarized?

$\Delta u(x)$

$\Delta d(x)$

$\Delta s(x)$

$\mu^2 = 2.5$ GeV$^2$

$x=0.2$
SIDIS at NLO

\[
\Delta \sigma^h = \sum_i e_i^2 \Delta q_i \left[ 1 + \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes \right] D_{qi}^h
\]

\[
+ \left( \sum_i e_i^2 \Delta q_i \right) \otimes \frac{\alpha_s}{2\pi} \Delta C_{qg} \otimes D_{G}^h + \Delta G \otimes \frac{\alpha_s}{2\pi} \Delta C_{gq} \otimes \left( \sum_i e_i^2 D_{qi}^h \right)
\]

- NLO global QCD-fit with inclusive and SIDIS data constrain \( \Delta q_i \) and \( \Delta G \).

NLO QCD global fits with inclusive DIS, SIDIS and p+p data, need inputs of:
- quark and gluon densities
- quark to hadron fragmentation functions
- gluon to hadron fragmentation functions
NLO Global -QCD Fit
DSSV2008

de Florian, Sassot, Stratmann, Vogelsang

- Inclusive DIS and SIDIS data.
- p+p inclusive hadron, jets.
- Frag. Func. from $e^+e^-$ data and fit to SIDIS multiplicities.
Urgently Need Precision SIDIS Data on Pol. $^3\text{He}$

HERMES-1996, the only $^3\text{He}$ SIDIS data

Polarized $^3\text{He}$ is an “effective” neutron target:

$^3\text{He} \approx S \approx S' \approx D$

$\sim 90\% \sim 1.5\% \sim 8\%$

In Deep-Inelastic Scattering:
two protons in $^3\text{He}$ contribute a dilution factor

effective polarization:

$$A_{^3\text{He}} = P_n(1-f_p)A_n + P_pf_pA_p$$

$$P_n = 0.86^{+0.036}_{-0.02}$$

$$P_p = -0.028^{+0.009}_{-0.004}$$

$$f_p = \frac{2\sigma_p}{\sigma_{^3\text{He}}}$$
Neutron $A^h_{1n}$ is sensitive to $\Delta d$, $\Delta \bar{d}$

Proton: $u$ $u$ $d$ Notation: $d = u_n$

$e^2_q$:

\[
\begin{array}{ccc}
\frac{4}{9} & \frac{4}{9} & \frac{1}{9} \\
\end{array}
\]

Neutron: $d_n$ $d_n$ $u_n$ $\Rightarrow$ $u$ $u$ $d$

$e^2_q$:

\[
\begin{array}{cccc}
\frac{1}{9} & \frac{1}{9} & \frac{4}{9} & \frac{1}{9} \\
\end{array}
\]

Polarized deuteron is not as good as $^3$He:

pol. deuteron $\approx$ pol. proton + pol. neutron

- Spin effects likely to cancel between proton and neutron, leading to smaller asymmetry signals.
- $u$-quarks dominate in deuteron, less sensitive to $d$-quarks.
- ND$_3$ target lower polarization, lower luminosity, worse dilution factor.
Neutron $A_{1n}^h$ is most sensitive to $\Delta d$, $\Delta \bar{d}$

$$\frac{\sigma_q}{\sigma_{all}} = e_f^2 q_f \cdot D_f^h / \sum e_i^2 q_i \cdot D_i^h$$

($@ z_h = 0.5$)

u-quark dominates in proton

d-quark’s effects show up in neutron
The Big News From STAR

$\Delta \bar{u}$ a shift away from the current best mean value was observed.

$W^-$ data at $\eta<0$ tend to lie above central curve based on DSSV2008

$\Delta \bar{u} > \Delta \bar{d}$ preferred for $x = 0.05 \sim 0.2.$

Strong indications of non-vanishing sea quark polarizations at $x=0.05 \sim 0.2$

A major effort at RHIC, DOE milestone. Both PHENIX and STAR are expected to release their final Run2011+Run2012+Run2013 W asymmetry results soon.
STRA W data introduced shifts to sea polarization in NLO global fit
Statistical Model prediction. Bourrely, Buccella, Soffer
PLB 726, 296 (2013)

BBS2008: a rather large sea polarization 10~20%, strong flavor dependency.
Neutron $A_{1n}^h$ is most sensitive to $\Delta d$, $\Delta \bar{d}$.

Urgently Need Precision SIDIS Data on Pol. Neutron ($^3$He).
Experiment Setup: BigBite+Super_BigBite

- Spectrometer layout of SIDIS
- Independent electron and hadron arms:
  - Large momentum bite
  - Moderate solid angle
  - High-rate capability
  - Excellent PID
- \( h^+/h^- \) symmetric acceptance

\[ E_0 = 11, ~ 8.8 \text{ GeV} \] 30 days
\[ \text{SBS @14}^\circ, \text{ 10}^\circ \]
$<Q^2>$ of SBS+BB SIDIS: > HERMES, < COMPASS
Acceptances: $Q^2, z, p_{T}^{h}, \phi_{h}$ vs $x$

$Q^2 \geq 1 \text{ GeV}^2, W \geq 2 \text{ GeV}, M_{X} \geq 1.5 \text{ GeV}, y \leq 0.9, P_{h} \geq 2 \text{ GeV}$
Electron Arm—BigBite Spectrometer

**BigBite @ 6 GeV (E06-010 transversity expt):**
- Three MWDCs for tracking (18 wire planes)
- Pre-shower/shower calorimeter for trigger and PID
- Scintillator hodoscope for timing
- Dipole magnet: B*dl=1 T*m

**BigBite @ 12 GeV:**
- Detector upgrades including:
  - GEM chambers for high-rate, high-resolution tracking (resolve higher electron momenta at same field integral)
  - Gas Cherenkov for higher-fidelity e/π separation
  - New detector support frame
- **BigBite parameters in E12-14-008:**
  - Central angle = 30 deg.
  - Target to magnet yoke distance = 1.5 m
Projected Neutron Asymmetry-1D $E_0=11$ GeV

- Projected asymmetry precisions (stat. only) in $A_{1n}^h$ vs $x$, integrated over $z$, $p_T$,
- Compared to prediction of “DSSV+” NLO global fit, arXiv:1108.3955
Projected Asymmetry Precision-2D (x, z), $E_0=11$ GeV

- High precision measurements on a dense grid of (x, z).
- Consistent deviations from NLO QCD prediction?
Results of a DSSV study, impacts on error bands of sea quark polarization:

- Slight reduction on $\bar{u}$
- Very significant reduction on $\bar{d}$
- Noticeable reduction on $s = \bar{s}$

Black: width of parabolas at a 2% increase of the DSSV $\chi^2$ ($\sim 1\sigma$).
Red: adding this experiment.
Physics Impacts:
Leading-Order “Purity” Method

Precisely determine \( \Delta u/u \) and \( \Delta d/d \)

Significantly improve \( \Delta \bar{u}/\bar{u} \)

Potential of discovery:
\( \Delta \bar{d}/\bar{d} \neq 0 \)
Potential of Discovery $\Delta \bar{d}/\bar{d} \neq 0$

Statistical Model
$Q^2 = 4.0 \text{ GeV}^2$

This experiment (purity)
- $E_0 = 11 \text{ GeV}$
- $E_0 = 8.8 \text{ GeV}$
Leading-Order “Purity” Method

Sensitivity to Strangeness

Assuming LO interpretation, and known Frag. Func.
\[ \int_{0}^{1} (\bar{d} - \bar{u}) \, dx = 0.118 \pm 0.012. \]

Many models explain \( \bar{d} - \bar{u} \), including the meson-cloud model (\( \pi \)) which predicts \( \Delta \bar{u} = \Delta \bar{d} = 0 \).

Pauli-blocking model:
\[ \int_{0}^{1} [\Delta \bar{u}(x) - \Delta \bar{d}(x)] \, dx = \frac{5}{3} \cdot \int_{0}^{1} [\bar{d}(x) - \bar{u}(x)] \, dx \approx 0.2. \]

Polarized sea flavor asymmetry: non-perturbative in nature, intrinsic property of nucleon.
§ Exploratory study

Removing $O(M_N^n/P_Z^n)$ errors + $O(\alpha_s)$

D. de Florian et al.
PRD 80, 034030 (2009)

P. Jimenez-Delgado et al.

We found $\Delta \bar{u} > \Delta \bar{d}$ with large sea asymmetry

$$\int dx \left( \Delta \bar{u}(x) - \Delta \bar{d}(x) \right) \approx 0.24(6)$$
**Summary: Δq Experiment**

Precision $A^h_{1n}$ and multiplicity data on a dense grid of $(x,Q^2,z)$:

- Strong constraints on $Δq$ through NLO QCD global fits.
- Leading-Order “purity”-method $Δq$ extraction, as in HERMES and COMPASS.
- Flavor non-singlet observables which are only sensitive to valence $Δq_v$
- Self-consistency cross-checks to set limits on interpretation systematics.

Complimentary to CLAS12 SIDIS measurements on NH$_3$ and ND$_3$ targets.
Complimentary to SoLID $^3$He target, with a higher-$Q^2$ coverage

**STAR W$^-$ data suggests a non-vanishing sea polarization:**

$Δ\bar{u} > 0$, $Δ\bar{u} > Δ\bar{d}$? 

**Neutron $A^h_{1n}$ is most sensitive to $Δd$, $Δ\bar{d}$**

**Potential of Discovery** $Δ\bar{d}/\bar{d} ≠ 0$

SBS project has been approved by DOE.
Target, spectrometer and detector constructions are underway.
Can run within the first five years of JLab-12GeV.
Backup Slides
High-Luminosity Polarized $^3$He Target

Basic Target Parameters:

- Polarization: 60-65% based on alkali-hybrid spin-exchange optical pumping technology
- Beam current: 40 $\mu$A
- Target cell length along beam-line: 60 cm
- Electron-polarized neutron luminosity:
  - Luminosity * Pol.$^2$ capability upgraded (relative to previous targets) by using convection-driven circulation of gas between “pumping chamber” and “target chamber” (already demonstrated in bench tests) and metal end-windows to prevent cell rupture (under development)
- Spin orientation in “any” direction; holding field $\sim$25 G
- Fast spin rotation: Change spin orientation every $\sim$120 s.

Conceptual design of SIDIS target w/metal end windows

Same as in SBS-Transversity (E12-09-018), except target spin in longitudinal direction.
Leading-Order Christova-Leader Method

\[(\Delta d_v - \frac{1}{4}\Delta u_v)_{LO} = \frac{1}{4}(7u_v + 2d_v)A_{1He}^{\pi^+ - \pi^-}\]

\[A_{1He}^{\pi^+ - \pi^-} = \frac{\Delta \sigma_{He}^{\pi^+} - \Delta \sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+} - \sigma_{He}^{\pi^-}} = \frac{X}{1 - r} \cdot \frac{A_{1He}^{\pi^+}}{A_{1He}^{\pi^-}} \cdot \frac{\sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+}} \cdot \frac{\sigma_{He}^{\pi^+}}{\sigma_{He}^{\pi^-}}
\]

\[\left[\Delta \bar{u}(x) - \Delta \bar{d}(x)\right]_{LO} = 3\left[g_1^p(x) - g_1^n(x)\right] - \frac{1}{2}\left(\Delta u_v - \Delta d_v\right)_{LO}\]
HERMES and COMPASS $A^{h}_{1N}$

Assume:
Leading order $x$-$z$ separation and current fragmentation.
Isospin symmetry and charge conjugation.
Purity from Monte Carlo.

Solve for $\vec{A} = P^h_f(x) \cdot \vec{Q}$

$\vec{A} = (A^\pi_{1p}, A^\pi_{1p}, A^{K+}_{1p}, A^\pi_{1d}, A^{K+}_{1d}, A^\pi_{1p}, A^{K-}_{1p}, A^{K-}_{1d}, A_{1p}, A_{1d})$