Polarized electron-deuteron deep-inelastic scattering with spectator nucleon tagging

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in collaboration with Ch. Weiss,
JLab LDRD project on spectator tagging
WC, C. Weiss, arXiv:1906.11119
Electron-ion collider

- World's first polarised electron-proton/light ion and electron-nucleus collider. Two sites under consideration: Jefferson Lab and Brookhaven National Lab, USA. → talks by S. Fazio, P. Rossi on Fri.

- 2015 Nuclear Physics Long Range Plan: “[EIC] as the highest priority for new facility construction following completion of FRIB”
- 2017–18 National Academies of Science (NAS) Review
- Next stage: CD0 (formally establishing mission need), expected this year
- User meeting in Paris last week: https://indico.in2p3.fr/event/18281/
Why focus on light ions at an EIC?

- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - coherent phenomena

- Light ions have unique features
  - polarized beams
  - breakup measurements & tagging
  - first principle theoretical calculations of initial state

- Intersection of two communities
  - high-energy scattering
  - low-energy nuclear structure

Use of light ions for high-energy scattering and QCD studies remains largely unexplored
EIC design characteristics (for light ions)

- CM energy $\sqrt{s_{eA}} = \sqrt{Z/A}$ $20 - 100 \text{GeV}$
  - DIS at $x \sim 10^{-3} - 10^{-1}$, $Q^2 \leq 100 \text{GeV}^2$

- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables

- Polarized light ions
  - $^3\text{He}$, other @ eRHIC
  - $d$, $^3\text{He}$, other @ JLEIC (figure 8)
  - spin structure, polarized EMC, tensor pol, ...

- Forward detection of target beam remnants
  - diffractive and exclusive processes
  - coherent nuclear scattering
  - nuclear breakup and tagging
  - forward detectors integrated in designs
Light ions at EIC: physics objectives

- **Neutron structure**
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects

- **Nucleon interactions in QCD**
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation

- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

Need to control nuclear configurations that play a role in these processes
Theory: high-energy scattering with nuclei

- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$

- Scales can be separated using methods of light-front quantization and QCD factorization

- Tools for high-energy scattering known from $ep$

- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron
  - still low-energy nuclear physics, just formulated differently

Frankfurt, Strikman '80s
Kondratyuk, Strikman, NPA '84
Neutron structure measurements

Needed for flavor separation, singlet vs non-singlet evolution etc.

- EIC will measure **inclusive** DIS on light nuclei \([d, ^3\text{He}, ^3\text{H}(?)]\)
  - Simple, no FSI effects
  - Compare \(n\) from \(^3\text{He}\) ↔ \(p\) from \(^3\text{H}\)
  - Comparison \(n\) from \(^3\text{He}, d\)

- **Uncertainties** limited by nuclear structure effects
  → binding, Fermi motion, non-nucleonic dof

- \(^3\text{He}\) is in particular affected because of intrinsic \(\Delta s\)

If we want to aim for precision, use tools that avoid these complications
Neutron structure with tagging

- Proton tagging offers a way of controlling the nuclear configuration

- Advantages for the deuteron
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable

- Allows to extract free neutron structure with pole extrapolation
  - Eliminates nuclear binding and FSI effects
  - [Sargsian, Strikman PLB ’05]

- Suited for colliders: no target material \((p_p \rightarrow 0)\), forward detection, polarization.
  - fixed target CLAS BONuS limited to recoil momenta \(\sim 70\,\text{MeV}\)
Theoretical Formalism

- General expression of SIDIS for a polarized spin 1 target
  - Tagged spectator DIS is SIDIS in the target fragmentation region
    \[ \vec{e} + \vec{T} \rightarrow e' + X + h \]

- Dynamical model to express structure functions of the reaction
  - First step: impulse approximation (IA) model
  - Results for longitudinal spin asymmetries
  - FSI corrections (unpolarized \textit{Strikman, Weiss PRC '18})

- Light-front structure of the deuteron
  - Natural for high-energy reactions as \textit{off-shellness of nucleons} in LF quantization remains \textit{finite}
Polarized deuteron tagged DIS: cross section

- Spin 1 particle has density matrix with 8 parameters: 3 vector, 5 tensor

- SIDIS cross section: unpolarized + vector polarized can be copied from spin 1/2 [Bacchetta et al., JHEP ('07)]
  Tensor part has 23 additional structure functions, each with their unique azimuthal dependence [WC, C. Weiss, in prep.]

- In the impulse approximation all SF can be written as

\[
F^k_{ij} = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2)\text{or} g_{1,2}(\tilde{x}, Q^2)\} \times \{\text{bilinear forms in deuteron radial wave function} f_0(k), f_2(k)\}
\]

- In the IA the following structure functions are zero → sensitive to FSI
  - beam spin asymmetry \(F^\sin \phi_h\)
  - target vector polarized single-spin asymmetry [8 SFs]
  - target tensor polarized double-spin asymmetry [7 SFs]
Polarized structure function: longitudinal asymmetry

- On-shell extrapolation of double spin asymmetry
  - Nominator
    \[ d\sigma_\parallel \equiv \frac{1}{4} \left[ d\sigma(\frac{1}{2},+1) - d\sigma(-\frac{1}{2},+1) - d\sigma(\frac{1}{2},-1) + d\sigma(-\frac{1}{2},-1) \right] \]
  - Two possible denominators: 3-state and 2-state
    \[ d\sigma_3 \equiv \frac{1}{6} \sum_{\Lambda_e} [d\sigma(\Lambda_e,+1) + d\sigma(\Lambda_e,-1) + d\sigma(\Lambda_e,0)] \]
    \[ d\sigma_2 \equiv \frac{1}{4} \sum_{\Lambda_e} [d\sigma(\Lambda_e,+1) + d\sigma(\Lambda_e,-1)] \]
  - Asymmetries: **tensor polarization** enters in 2-state one
    \[ A_{||,3} = \frac{d\sigma_\parallel}{d\sigma_3} [\phi_h \text{ avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L} \]
    \[ A_{||,2} = \frac{d\sigma_\parallel}{d\sigma_2} [\phi_h \text{ avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})}} \]

- Impulse approximation yields in the Bjorken limit \[ \alpha_p = \frac{2p_p^+}{p_D^+} \]
  \[ A_{||,i} \approx D_i(\alpha_p, |p_{pT}|) A_{\parallel n} = D_i(\alpha_p, |p_{pT}|) \frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1 + \epsilon R_n)F_{1n}(\tilde{x}, Q^2)} \]
**Nuclear structure factors $D_2$, $D_3$**

- $D_2$ has physical interpretation as ratio of nucleon helicity density to unpolarized density in a deuteron with polarization $+1$. $D_3$ has no such interpretation.

![Graph showing $D_3$ and $D_2$ vs $p_{pt}$](image)

- **Bounds:** $-1 \leq D_2 \leq 1$
- **Due to lack of OAM** $D_2 \equiv 1$ for $p_T = 0$
- **Clear contribution from D-wave at finite recoil momenta**
- **$D_3$ violates bounds due to lack of tensor pol. contribution**
- **$D_3 \neq 0$ for $p_T = 0$**
- **$D_2$ closer to unity at small recoil momenta**
- **2-state asymmetry is also easier experimentally!!**

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Tagging: simulations of pole extrapolation of $A_{||}$

Neutron spin structure with tagged DIS $\bar{e} + \bar{D} \rightarrow e' + p(\text{recoil}) + X$

EIC simulation, $s_{eN} = 2000$ GeV$^2$, $L_{\text{int}} = 100$ fb$^{-1}$

Nuclear binding eliminated through on-shell extrapolation in recoil proton momentum

$Q^2 = 10^{-16}$, $6^{-10}$, $4^{-6}$, $2.5^{-4}$

Error estimates include extrapolation uncertainty

Statistics requirements
- Physical asymmetries $\sim 0.05 - 0.1$
- Effective polarization $P_eP_D \sim 0.5$
- Luminosity required $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$

As depolarization factor
\[ D = \frac{y(2-y)}{2-2y+y^2} \] and $y \approx \frac{Q^2}{xs_{eN}}$, wide range of $s_{eN}$ required!

Precise measurement of neutron spin structure
- separate leading- /higher-twist
- non-singlet/singlet QCD evolution
- pdf flavor separation $\Delta u, \Delta d$. $\Delta G$ through singlet evolution
- non-singlet $g_{1p} - g_{1n}$ and Bjorken sum rule

https://www.jlab.org/theory/tag/
Final-state interactions modify cross section away from the pole

- studied for unpolarized case at EIC kinematics, pole extrapolation still feasible
  
  [Strikman, Weiss PRC ’18]

- dominated by slow hadrons in target fragmentation region of the struck nucleon

- extend to $\vec{e} + \vec{d}$

- constrain FSI models

- non-zero azimuthal and spin observables through FSI

Tensor polarized observables

Tagging with complex nuclei $A > 2$

- isospin dependence, universality of bound nucleon structure

- $A - 1$ ground state recoil

Resolved final states: SIDIS on neutron, hard exclusive channels
Conclusions

- Light ions address important parts of the EIC physics program

- Tagging and nuclear breakup measurements overcome limitations due to nuclear uncertainties in inclusive DIS → precision machine

- Unique observables with polarized deuteron: free neutron spin structure, tensor polarization

- Clear advantages in using two-state asymmetry to extract $g_{1n}$

- Extraction of nucleon spin structure in a wide kinematic range

- Lots of extensions to be explored!