Polarized light ion physics

Objectives and challenges
Control nuclear configurations!

Deuteron and spectator tagging
Cross section \(e + d \rightarrow e' + p + X\)
Polarized deuteron structure

Applications at EIC
Free neutron structure with tagging
Neutron spin structure with tagging
Tensor-polarized asymmetries
Initial-state modifications EMC effect

Idea: Control nuclear configuration during high-energy process through spectator detection

→ Identify active neutron or proton
→ Control nuclear interactions, modifications
→ Control neutron polarization, S/D wave

This presentation:
Review tagging with unpolarized deuteron at EIC
Discuss opportunities with polarized deuteron

Technical realization
**Light ions: Physics objectives**

**Neutron spin structure**
- Flavor decomposition of quark PDFs/spin, GPDs, TMDs
- Singlet-nonsinglet separation in QCD evolution for $\Delta G$

**Nuclear interactions**
- Hadronic: Short-range correlations, NN core, non-nucleonic DoF
- Partonic: Nuclear modification of partonic structure
  - EMC effect $x > 0.3$, antishadowing $x \sim 0.1$
  - Quarks/antiquarks/gluons? Spin, flavor? Dynamical mechanism?

**Coherent phenomena**
- Nuclear shadowing $x \ll 0.1$
- Buildup of coherence, interaction with 2, 3, 4... nucleons?
  - Shadowing and saturation in heavy nuclei

[Nucleus rest frame view]
Light ions: Deuteron and spectator tagging

Deuteron as simplest system

- Nucleonic wave function simple, well known \((p \sim < 400 \text{ MeV})\)
- Nucleons spin-polarized, some D-wave depolarization
- Non-nucleonic DoF suppressed: \(\Delta\) isobars, \(\pi\)
  - Frankfurt, Strikman 81. Large \(\Delta\) component in \(^3\text{He} \rightarrow\) see below

Spectator nucleon tagging

- Identifies active nucleon
- Controls configuration through recoil momentum:
  - spatial size \(\rightarrow\) interactions, \(S/D\) wave \(\rightarrow\) polarization
- Average configurations \(~\) few \(10 - 100 \text{ MeV}\)
- Small-size configurations \(~\) 200-500 MeV
- Fixed-target experiments: JLab BONuS 6/12 GeV, ALERT (protons), BAND (neutrons)
Spectator moves forward in ion beam direction

Spectator longitudinal momentum in detector controlled by light-cone fraction in deuteron rest frame:

\[
p_{\parallel p}[\text{det}] \approx \frac{P_D}{2} \left( 1 + \frac{P_{p\parallel}[\text{rest}]}{m} \right)
\]

large offset, can be detected

Far-forward detectors

Magnetic spectrometer for protons, integrated in beam line, several subsystems: good acceptance and resolution

Zero-Degree Calorimeter for neutron

Advantage over fixed target: No target material, can detect spectators with rest frame momenta down to \(~0\)

Ion polarization prepared in beam, no holding magnets

Physics-detector simulations (unpolarized)
Jentsch, Tu, Weiss, PRC 104, 065205 (2021)
EIC Yellow Report 2021 [INSPIRE]
Tagging: Cross section

\[ \frac{d\sigma}{dxdQ^2(d^3p/E_p)} = \text{Flux} \times \sum \text{Kin}(y) \times F_d(x, Q^2; \alpha_p, p_{pT}) \times \text{Harmonic}(\phi_p) \]

Semi-inclusive cross section \( e + d \rightarrow e' + X + p \) (or \( n \))

Collinear frame: Virtual photon and deuteron momenta collinear \( q \parallel p_d \), along \( z \)-axis

Proton recoil momentum described by light-cone components: \( p_p^+ = \alpha_p p_d^+ / 2 \), \( p_{pT} \)
Related in simple way to rest-frame 3-momentum

Here: No assumption re composite nuclear structure, \( A = \sum N \), or similar!

Jeschonnek, Ford, Van Orden 2013
Cosyn, Weiss 2020
Tagging: Cross section spin dependence

\[ \sigma = \sum_{\lambda, \lambda'} \rho_{\lambda\lambda'} \langle d, \lambda' \rangle \cdots \langle d, \lambda \rangle \]

Deuteron polarization

Spin-1 density matrix \( \rho_{\lambda'\lambda}(S, T) \)

3 vector, 5 tensor parameters

Fixed by beam polarization measurements

Polarized cross section

Average with deuteron spin density matrix

\( U + S + T \) structures

U + S cross section has same form and \( \phi_p \)-dep as for spin-1/2 target

Bacchetta et al 2007

T cross section has 23 new structures, some with \( \phi_p \)-dep unique to T polarization

Integration over tagged proton momentum: Recover inclusive tensor-polarized structures \( b_1 \ldots b_4 \)

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Integration over tagged proton momentum: Recover inclusive tensor-polarized structures \( b_1 \ldots b_4 \)

Cosyn, Weiss, PRC102 (2020) 065204 + in preparation (2023)

Invariant formulation, suitable for collider and fixed-target

General result, valid for any spin-1 target
Deuteron light-front structure

- pn wave function at fixed light-front time $x^+ = x^0 + x^3$
- Permits matching with high-energy/DIS processes on nucleon [Frankfurt, Strikman 80s]
- Contains low-energy nuclear structure ← NN interactions

Polarized deuteron light-front wave function

- Spins described by light-front helicity states
- Light-front WF constructed from 3D WF in pn CM frame, including transformation of spin states (Melosh rotation)
- Contains S and D waves
**Tagging: DIS process**

**Impulse approximation**

Spectator and DIS final state evolve independently

\[
d\sigma[ed \to e'Xp] = S_d(\alpha_p, p_{pT}) \, d\Gamma_p \times d\sigma[en \to e'X]
\]

\[
S_d(\alpha_p, p_{pT}) = \text{Flux}(\alpha_p) \times |\Psi_d(\alpha_p, p_{pT})|^2 \quad \text{spectral function}
\]

**Final-state interactions**

Part of DIS final state interacts with spectator, transfers momentum

Requires theoretical modeling \(\to\) later

For DIS in scaling regime \(\nu, Q^2 \to \infty\): These approximations are consistent with leading twist factorization of \(\sigma[eN]\), partonic sum rules, etc.
Tagging: Deuteron spectral function

Deuteron spectral function

Describes distribution of neutrons depending on tagged proton momentum $\alpha_p, p_{pT}$

Depends on deuteron and neutron spin

Satisfies momentum and spin sum rules

Neutron polarization in deuteron

Effective neutron polarization depends on tagged proton momentum: S vs D wave

Example: Deuteron in pure spin state +1. Plot shows probability that neutron has helicity +1/2 i.e. is polarized along deuteron spin direction

Tagged proton momentum controls effective neutron polarization!

Cosyn, Weiss PLB799 (2019) 135035; PRC102 (2020) 065204
Applications: Free neutron structure

Reaching free nucleons

Physical spectator momenta: NN configs have finite size, nucleons interact

Analytic continuation to unphysical momenta $|\mathbf{p}_p|^2 < 0$ can reach configs with “infinite” size, nucleons free!
Bethe-Peierls pole in momentum, asymptotic S-wave at large distances

Light-front wave function: Pole at $p_{pT}^2 < 0$

[Feynman diagram: Neutron on mass shell if 4-momentum $p_n^2 = (p_d - p_p)^2 = m^2$]

Extraction procedure

Measure proton-tagged cross section at fixed $\alpha_p$ as function of $p_{pT}^2 > 0$

Divide data by pole term of spectral function

Extrapolate to pole position $p_{pT}^2 \rightarrow -a_T^2 < 0$

Simulated at EIC, appears feasible
Applications: Effective neutron polarization

\[ A_{\parallel,d}(x_n, Q^2; \alpha_p, p_{pT}) \quad \text{tagged longitud double spin asymmetry} \]

\[ = \frac{d\sigma_{\parallel}(+\frac{1}{2}, +1) - d\sigma_{\parallel}(\frac{1}{2}, +1) - d\sigma_{\parallel}(+\frac{1}{2}, -1) + d\sigma_{\parallel}(\frac{1}{2}, -1)}{d\sigma_{\parallel}(+\frac{1}{2}, +1) + d\sigma_{\parallel}(\frac{1}{2}, +1) + d\sigma_{\parallel}(+\frac{1}{2}, -1) + d\sigma_{\parallel}(\frac{1}{2}, -1)} \]

\[ = \frac{S_d(\alpha_p, p_{pT})[S]}{S_d(\alpha_p, p_{pT})[U + T]} A_{\parallel,n}(x_n, Q^2) \]

\[ D_d(\alpha_p, p_{pT}) \quad \text{effective neutron polarization, depends on tagged proton momentum} \]

D wave drops out at \( p_{pT} = 0 \):
Pure S-wave, neutron 100% polarized

D wave dominates at \( p_{pT} \sim 400 \text{ MeV} \):
Neutron polarized opposite to deuteron spin!

Tagged proton momentum controls effective neutron polarization in deuteron

Frankfurt, Strikman 1983
Cosyn, Weiss PLB799 (2019) 135035; PRC102 (2020) 065204
**Applications: Tensor polarized asymmetry**

Maximal tensor polarization can be achieved at $300$ MeV and $A_{zz} = 1$

$$
\alpha_p \cdot p_{pt} \approx \alpha_p = 1
$$

Much larger tensor asymmetry than in untagged scattering where most events come from nucleon momenta $\sim$ few 10 MeV and D-wave is small
Applications: More polarization observables

**Transverse vector polarization of deuteron**

Induces transverse nucleon polarization (transversity) deforms longitudinal nucleon polarization (spin-orbit)

Tagged measurements of $g_{2n}$ neutron spin structure function?
Challenge for light-front method. Involves “bad components” of EM current

**Final-state interactions**

Large effects at $p_{pT} > 300$ MeV, should be included in calculations of tagged spin observables

Description based on space-time picture in deuteron rest frame: Fast and slow hadrons
Strikman, Weiss PRC97 (2018) 035209

$\phi_{p}$ dependent tagged cross section includes T-odd structures: Zero in impulse approximation, require final state interactions, can provide sensitive tests (→ Sivers effect in SIDIS)
Applications: Tagged EMC effect

EMC effect

Modification observed in nuclear DIS $0.3 < x < 0.7$

What NN distances/momenta cause modification?

Control configurations with tagging!

EIC simulations

Use proton and neutron tagging

$\alpha_{p,n} > 1, p_T \sim \text{few 100 MeV}$

Initial-state modifications and final-state interactions are of the same order, need strategy for separation

Simulations including statistics, optimization of analysis

Jentsch, Tu, Weiss, in progress

Could be extended to polarized deuteron
Deuteron polarization at EIC

Present EIC design provides polarized proton and 3He beams for spin physics
EIC Yellow Report 2021 [INSPIRE]

Deuteron’s small anomalous magnetic moment makes manipulation of its spin in synchrotron very challenging, requires high magnetic field. Not possible with present full Siberian Snake design.

Technical possibilities for deuteron polarization exist and are being studied
Recent update: Huang, Méot, Ptitsyn, Ranjbar, Roser, Report at IPAC 2021 [INSPIRE]

Deuteron polarization could be considered in connection with a possible future EIC facility upgrade
Summary

- Spectator tagging with deuteron permits control of nuclear configuration in high-energy process and differential analysis of nuclear effects — new opportunities, new challenges for theory and experiment.

- Spectator tagging with unpolarized deuteron feasible with EIC far-forward detectors, studied in physics and detector simulations. Applications to free neutron structure, EMC effect, shadowing/diffraction at small x.

- Spectator tagging with polarized deuteron would enable several unique applications:
  - Control effective neutron polarization in vector-polarized deuteron, longitudinal or transverse.
  - Realize tensor-polarized asymmetries O(1).
  - Theory input on final-state interactions essential for interpretation, requires investment.

[Not covered here: Untagged DIS on polarized deuteron at EIC and impact on spin physics]

- Deuteron polarization at EIC considered technically possible, discussed as facility upgrade.

- Community should formulate polarized deuteron program for EIC and initiate technical development.
Supplemental material
EIC: Far-forward detectors

Magnetic spectrometer and detectors for charged particles, integrated in accelerator optics, several subsystems

Zero-degree calorimeter for neutrals

Subsystems used in spectator tagging

- **Protons**
  - $\theta < 5 \text{ mrad}$
  - $0.2 < x_L < 0.6$
  - **Off-mom detectors**

- **Protons**
  - $\theta < 5 \text{ mrad}$
  - $x_L > 0.6$
  - **Roman Pots**

- **Protons**
  - $5.5 < \theta < 20 \text{ mrad}$
  - **B0 tracker**

- **Neutrons**
  - $\theta < 4 \text{ mrad}$
  - **ZDC**

Proton acceptance = function($\theta, x_L$)

[This version EIC Yellow Report 2022; fur updates see EPIC Collaboration]
**EIC: Momentum resolution**

**Proton momentum resolution**

Simulations include detector resolution and beam effects: angular divergence, crabbing rotation, vertex smearing

Details depend on kinematics: Beam energy, subsystems used

Transverse momentum resolution achieved \( \Delta p_T \sim 20 \text{ MeV} \) at low \( p_T \)

Longitudinal momentum resolution typically \( \alpha_p/\alpha_p \lesssim 5\% \), significantly better for \( \alpha_p \sim 1 \)

Figures in supplement

**Neutron momentum resolution**

\[
\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E}} \oplus 5\% \quad \frac{\Delta \theta}{\theta} = \frac{3 \text{ mrad}}{\sqrt{E}}
\]

with present ZDC design
Tagged cross section measured with excellent coverage

Significant uncertainties in evaluation of pole factor due to $p_T$ resolution

Pole factor evaluated in event-averaged analysis (binned in $p_T^2$) to allow for correction of resolution effects (unfolding)

Uncertainties analyzed, results validated by comparison with input

Pole extrapolation realistic for proton spectator, exploratory for neutron spectator

Final uncertainties depend on ability to correct for resolution
Tagging: Bound nucleon structure - EMC effect

**EMC effect**

Observed in inclusive DIS $0.3 < x < 0.7$

What NN distances/momenta cause modification?

Control configurations with tagging!

**Estimate: Nucleon virtuality dependence**

![Diagram](image)

Parameters fixed by inclusive EMC effect data and average virtuality $\langle V \rangle_A \sim 2 \langle p^2 \rangle_A$ from nuclear structure calculations

Ciofi degli Atti, Frankfurt, Kaptari, Strikman 2007

Minimal model. Includes possibility that EMC effect generated by SRCs, but not limited to it

Modifications $\sim$20-30%, depending on $\alpha_p$ and $p_{pT}$

Initial-state modification vs final-state interactions?
Tagged EMC effect: Initial vs final state

$$\sigma = \int_{p_{pT}[\text{max}]} d^2p_T \, S_d(\alpha_p, p_T) \, \sigma_n(x_n)$$

Here: $$p_{pT}[\text{max}] = 0.4 \text{ GeV}$$

Compare EMC effect and FSI

Same order-of magnitude, requires careful assessment

EIC simulations including statistics, optimization of analysis

Jentsch, Tu, Weiss, in progress