Opportunities for tagged EMC studies with EIC

C. Weiss (JLab), 2nd SRC/EMC Workshop, MIT, 20-23 Mar 2019

- **Light ion physics at EIC**
  - Energy, luminosity, polarization, detection
  - Physics objectives

- **Deuteron and spectator tagging**
  - Theoretical models
  - EIC simulations unpolarized/polarized

- **Tagged EMC studies with EIC**
  - Proton tagging & momentum dependence
  - Neutron tagging
  - Polarized deuteron vector/tensor
  - $A > 2$ nuclei and breakup
  - Exclusive processes

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**EIC simulations:** JLab 2014/15 LDRD

[Webpage]

**Theory:** Continuing effort
Strikman, CW, PRC97 (2018) 035209 [INSPIRE]
+ in preparation
Light ions: EIC capabilities

- CM energy $\sqrt{s_{ep}} \sim 20–100$ GeV
  - Factor $\sqrt{Z/A}$ for nuclei
  - DIS at $x \gtrsim 10^{-3}$, $Q^2 \lesssim 10^2$ GeV$^2$

- Luminosity $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$
  - Exceptional configurations in target
  - Multi-variable final states
  - Polarization observables

- Polarized protons and light ions
  - eRHIC: pol $^3$He
  - JLEIC: pol $d$ and $^3$He with figure-8

- Forward detection of $p, n, A$
  - Diffractive and exclusive processes
  - Nuclear breakup and spectator tagging
  - Coherent nuclear scattering
Light ions: Physics objectives

- Neutron structure
  Flavor decomposition of PDFs/GPDs/TMDs, singlet vs. non-singlet QCD evolution, polarized gluon
  Eliminate nuclear binding, non-nucleonic DOF!

- Nucleon interactions in QCD
  Nuclear modification of quark/gluon densities
  Short-range correlations, non-nucleonic DOF
  QCD origin of nuclear forces
  Associate modifications with interactions!

- Coherent phenomena in QCD
  Coherent interaction of high–energy probe with multiple nucleons, shadowing, saturation
  Identify coherent response!

  Common challenge: Many possible nuclear configurations during high-energy process.
  Need to “control” configurations!
Light ions: Deuteron and spectator tagging

- Deuteron, incl. polarized
  - $pn$ wave function simple, known well
    - incl. light-front WF for high-energy procs
  - Neutron spin–polarized
    - Intrinsic $\Delta$ isobars suppressed by isospin $= 0$
      - $|\text{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$ negligible
      - 3He spin structure distorted by $\Delta$'s
        - Guzey, Strikman, Thomas et al 01

- Spectator nucleon tagging
  - Identifies active nucleon
  - Controls configuration through recoil momentum:
    - Spatial size, $S \leftrightarrow D$ wave
  - Typical momenta $\sim$ few 10 – 100 MeV (rest frame)

Tagging in fixed-target experiments
- CLAS6/12 BONUS, recoil momenta $p = 70$–150 MeV
- JLab12 ALERT, Hall A
Light ions: Deuteron and spectator tagging

\[ p_p^\parallel = \frac{1}{2} \left[ 1 + \mathcal{O} \left( \frac{p_p^{\text{rest}}}{m} \right) \right] \]

- Spectator tagging with colliding beams

  Spectator nucleon moves forward with approx. 1/2 ion beam momentum

  Detection with forward detectors integrated in interaction region and beams optics
  LHC \( pp/pA/AA \), Tevatron \( p\bar{p} \), RHIC \( pp \), ultraperiph. \( AA \)

- Advantages over fixed-target

  No target material, \( p_p^{\text{rest}} \rightarrow 0 \) possible

  Potentially full acceptance, good resolution

  Can be used with polarized deuteron

  Forward neutron detection possible

- Unique physics potential
Theoretical models for tagged DIS \( e + d \rightarrow e' + N + X \)

- **Unpolarized**: Light-front impulse approximation with realistic wave functions, final-state interactions \( x \gtrsim 0.1 \) \( \text{Strikman, CW, PRC97 (2018) 035209} \rightarrow \text{Talk Thursday} \)


- **Tensor-polarized deuteron**: General structure of response including azimuthal-angle dependence, polarization observables \( \text{Cosyn, Sargsian, CW, in progress} \)

- **Diffractive scattering \( x \ll 0.1 \)**: Theory of diffractive deuteron breakup including shadowing and low-momentum FSI \( \text{Guzey, Strikman, CW, in progress} \)

FORTRAN/C++ codes and documentation. Available at: [https://www.jlab.org/theory/tag/](https://www.jlab.org/theory/tag/)

Event generators and analysis tools

- **\( e + d \rightarrow e' + p + X \)** event generator: 4-vectors generated in collider frame.
  Includes crossing angle and intrinsic momentum spread in ion beam.
  Fixed-target applications possible \( \text{K. Park, Ch. Hyde} \)

- **Analysis tools**: Neutron structure, on-shell extrapolation

Forward detector model \( \rightarrow \) Following
Tagging with EIC: Unpolarized

- Measure tagged structure functions
  
  Recoil momentum dependence $\alpha_p, p_T$

  Uncertainty mainly systematic:
  Steep recoil momentum dependence, beam momentum spread
  LDRD project: Detailed estimates

- Extract free neutron structure

  On-shell extrapolation in $t - m^2 \leftrightarrow |p_{pT}|^2$

  Eliminates nuclear binding and FSI
  Sargsian, Strikman 05
  
  $F_{2n}$ extracted with few-percent accuracy

- Same measurements could be used to study tagged EMC effect

  Finite $|p_{pT}| \sim$ few 100 MeV

  Theoretical interpretation, EMC $\leftrightarrow$ FSI?
Tagging with EIC: Polarized

- Measure tagged spin asymmetries
  
  Momentum smearing/resolution effects largely cancel in asymmetry

  Physical asymmetries $\sim 0.05$-$0.1$, effective polarization $P_e P_D \sim 0.5$

  Possible with int lumi $\sim$ few 10 fb$^{-1}$

- Extract neutron spin structure
  
  D-wave drops out at $p_{pT} = 0$: Neutron 100% polarized

  Asymmetry depends weakly on off-shellness $t - m^2 \sim |p_{pT}|^2$

  On-shell extrapolation of asymmetry

- Same measurements can be used to study spin-dep EMC effect

Cosyn, CW arXiv:1902.03678
Tagged EMC studies with EIC*

- Recoil momentum dep of tagged structure fns
  What momenta/distances cause modification?
  Connection with $NN$ short-range correlations?
  Separate EMC ↔ FSI?

- Neutron tagging and modified proton structure
  Free proton structure known, serves as reference point
  Should be possible with forward neutron detectors.

- Vector-polarized tagged structure functions
  S vs. D waves, polarization observables.
  Spin-orbit effects in $\phi_p$ dependence.

- Tensor-polarized tagged structure functions
  Certain $\phi_p$ harmonics specific to tensor polarization, provide unique signal.
  Pure $N = 2$ effect. Complements inclusive $b_1$ structure function measurements.

* EIC will also enable non-tagged EMC measurements. Opportunities, specific challenges, need for discussion!
Tagged EMC studies with EIC II

- Tagging $\Delta$ isobars

  Tagged DIS $e + d \rightarrow e' + \pi + N$, reconstruct $\Delta$ from $\pi N$

  Direct demonstration of non-nucleonic degrees of freedom
  → Talk Strikman

- Tagging with complex nuclei $A > 2$

  Could test isospin dependence and/or universality of bound nucleon structure
  $(A - 1)$ ground state recoil, e.g. $3\text{He}$ ($e, e' d$) $X$

  Theoretically challenging, cf. experience with quasielastic breakup

- Tagged exclusive processes — meson production, DVCS

  Nuclear generalized parton distributions (GPDs).
  Measurements benefit from simpler final state, constrained kinematics ($\rightarrow$ FSI).

  Includes nuclear coherent processes $A \rightarrow A$
EIC simulations: Forward detection

- Forward detector integrated in IR and beam optics
  
  Protons/neutrons/fragments travel through ion beam quadrupole magnets
  
  Dispersion generated by dipole magnets
  
  Detection using forward detectors — Roman pots, ZDCs
  
  Tagging studies: Full acceptance, proton momentum resolution longit $\delta p/p \sim 10^{-3}$, angular $\delta \theta \sim 0.2$ mrad  
  
  P. Nadel-Turonski, Ch. Hyde et al.

- Intrinsic momentum spread in ion beam

  Transverse momentum spread $\sigma \sim$ few 10 MeV

  Smearing effect $p_{pT}(\text{vertex}) \neq p_{pT}(\text{measured})$, partly corrected by convolution

  Dominant systematic uncertainty in tagged neutron structure measurements. Correlated, $x$ and $Q^2$-independent.  
  
  JLab LDRD
Summary

- Light-ion physics program with EIC has great potential, should be developed & articulated at same level as $ep$ and $eA$(heavy)

- Spectator tagging permits nuclear DIS in controlled nuclear configuration: Neutron structure, EMC effect, coherent phenomena

- Interesting theoretical challenges

  Intersection of low-energy nuclear structure and high-energy scattering

  Workshop “Polarized light ion physics with EIC”, 5-9 Feb 2018, Ghent U, Belgium [webpage]

  Progress with final-state interactions, polarized deuteron, diffraction and shadowing

- Ready for simulations with next-generation physics models

  JLab 2014/15 LDRD project. Physics model codes publicly available at [webpage]. Open for collaboration!

- Needs further development/model implementation of forward detector