Physics opportunities with light ions at the EIC

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Why are light ions interesting?

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

- Light ions have unique features
  - polarized beams, different spins
  - 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 underexplored
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
Experimental apparatus: forward detection

The ePIC Detector

- Set of far-forward detectors
- Design and engineering challenge
- Useful across EIC physics program
  - exclusive coherent/incoherent diffraction
  - inclusive diffraction
  - ep target fragmentation
  - pion and kaon structure
- Light ions: measure breakup, “tag” particles
- Complementarity with second IR

A. Jentsch, ePIC collab. meeting
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
  - technical for $A > 3$ (Sokolov packing operators)

- Structure functions (IA) $F_A \propto F_N(\tilde{x}, Q^2) S(\alpha_p, p_{pT})$
Theory: nuclear structure calculations

- First principle NR calculations available for light ions
- Controlled expansion and hierarchy using $\chi$EFT for two- and three- body forces
- Variety of methods: finite-basis, no-core SM, GFMC, lattice EFT
- Fadeev methods for $^3$He reactions
- These tools need to be extended for applications in high-energy scattering
  - Light-front formulation of nuclear EFT techniques

LENPIC collab, arXiv:1807.02848
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

- Nucleon tagging offers a way of controlling the nuclear configuration

\[ t = (p_R - p_D)^2 \]

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

- Allows to extract \textbf{free} neutron structure with on-shell extrapolation \cite{Sargsian, Strikman PLB’05}

- \(^3\)He theoretically more complicated

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

- BUT needs much more theory input

- Measurements of neutron structure at an EIC over a wide kinematic range at few percent-level accuracy
On-shell extrapolation of $F_{2N}$

$$F_{2d} = [2(2\pi)^3] S_d(\alpha_p, p_{pT})[\text{unpol}] F_{2n}(\tilde{x}, Q^2)$$

Detailed simulations for EIC [Jentsch, Tu, Weiss, PRC 21]
Polarized structure function $g_{1n}$: longitudinal asymmetry

- Pole extrapolation of double spin asymmetry
  - Nominator
    \[ d\sigma_{\parallel} \equiv \frac{1}{4} \left[ d\sigma(+\frac{1}{2}, +1) - d\sigma(-\frac{1}{2}, +1) - d\sigma(+\frac{1}{2}, -1) + d\sigma(-\frac{1}{2}, -1) \right] \]
  - Denominators: 2-state
    \[ d\sigma_{2} \equiv \frac{1}{4} \sum_{e} [d\sigma(e, +1) + d\sigma(e, -1)] \]
  - $\lambda_d = 0$ state not needed!
- Impulse approximation yields in the Bjorken limit
  \[ \alpha_p = \frac{2p_p^+}{p_d^+} \]

\[ A_{\parallel,2} = \frac{d\sigma_{\parallel}}{d\sigma_{2}} [\phi_h \text{ avg}] \approx D_i(\alpha_p, |p_{pT}|)A_{\parallel,n} = D_2(\alpha_p, |p_{pT}|) \frac{D_{\parallel}g_{1n}(\tilde{x}, Q^2)}{2(1 + \epsilon R_n)F_{1n}(\tilde{x}, Q^2)} \]
Tagging: polarized neutron structure

- On-shell extrapolation of double spin asymmetry

\[ A_\parallel \approx D_2(\alpha_p, |p_pT|) A_{\parallel n} = D_2(\alpha_p, |p_pT|) \frac{D_{\parallel g_1n(\tilde{x}, Q^2)}}{2(1 + \epsilon R_n) F_{1n}(\tilde{x}, Q^2)} \]

- \( D_2 \) quantifies neutron depolarization due to nuclear structure
- \( D_2 \) depends on spectator kinematics \( \alpha_p, p_pT \)
- \( D_2 = \Delta S_d[\text{pure} +1]/S_d[\text{pure} +1] \) has probabilistic interpretation

\[ D_2 \]

- 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
- \( D_2 \) close to unity at small recoil momenta

WC, C. Weiss, PLB ('19); PRC ('20)
Tagging: polarized neutron structure

- **On-shell extrapolation** of double spin asymm.

\[ A_{||} = \mathcal{D}_2(\alpha_p, |p_{pT}|) \frac{D_{||} g_{1n}(\tilde{x}, Q^2)}{2(1 + \epsilon R_n) F_{1n}(\tilde{x}, Q^2)} \]

- D-wave suppr. at on-shell point
  \[ \rightarrow \text{neutron } \sim 100\% \text{ polarized} \]

- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)

- Statistics requirements
  - Physical asymmetries \( \sim 0.05 - 0.1 \)
  - Effective polarization \( P_e P_D \sim 0.5 \)
  - Luminosity required \( \sim 10^{34} \text{cm}^{-2} \text{s}^{-1} \)

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https://www.jlab.org/theory/tag/
Double spectator nucleon tagging \((p, n)\) with \(^3\text{He}\)

- Reduced uncertainties for tagged \(A_1\)
- Simplified treatment of nuclear corrections
  (no FSI between \(n - p\); \(\Delta\)-components in \(^3\text{He}\))
Issue in tagging: DIS products can interact with spectator $\rightarrow$ rescattering, absorption

Dominant contribution at intermediate $x \sim 0.1 - 0.5$ from "slow" hadrons that hadronize inside nucleus $\rightarrow ep$ target fragmentation measurements

Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.

FSI vanish at the pole $\rightarrow$ on-shell extrapolation still feasible
Nucleon interactions

How do nucleon interactions emerge from QCD?

- **Short-range structure** of nuclei, $NN$ force at very short distances
  - Quasi-elastic $d$ breakup
  - Short-range correlation studies: (multi-)nucleon knockout with high ($>k_F$) initial momenta, 3N correlations?

- **Medium modification** of nucleon properties embedded in nucleus: EMC effect, other quantities
  - $Q^2$, isospin ($N \neq Z$) dependence
  - gluon EMC effect
  - spin-dependent EMC effect on polarized light ions
  - tagging: what intra-nucleon distances play a role?

JLab12 will measure some of these processes, but open questions will remain that can be addressed at EIC
Diffractive deuteron break up: gluon density modification

- Double spectator tagging in forward detectors
- Study gluon densities as a function of initial nucleon momenta
- FSI treatment not included

BeAGLE

![Graph](image)

Z. Tu et al, PLB’21
Double spectator tagging in forward detectors

Study gluon densities as a function of initial nucleon momenta

FSI treatment not included

Z. Tu et al, PLB’21
Diffractive deuteron break up at large $p_T$: theory study

- Large $p_T$ between nucleons in final state $\rightarrow$ FSI
- LO calculation, gluon singlet and octet contributions
- Distinguish between different SRC dynamics
Nuclear interactions: Coherence

- Interaction of high-energy probe with coherent quark-gluon fields

- **Shadowing** is manifestation of coherence
  - **Diffractive** DIS at $x \ll 0.1$: 10-15% of events at HERA
  - **Interference** between diffractive amplitudes → reduction of cross section, leading twist
  - Extensively studied in heavy nuclei
  - Is especially clean in the **deuteron**, effects can be calculated
  - **Dynamics** of shadowing can be explored in tagging: **single** and **double**
  - Tagging also results in **FSI** between the slow $n$ and $p$

\[
\begin{align*}
  x, Q^2, \frac{1}{x} & \quad X \\
  x_p, k_T & \quad N \rightarrow N' \\
\end{align*}
\]

\[
\begin{align*}
  d & \quad \psi_d \quad n \quad p \\
  x & \quad + \quad x \\
\end{align*}
\]

\[
\begin{align*}
  \times \quad \text{FSI} \\
\end{align*}
\]

\[
\begin{align*}
  \text{interference} \\
\end{align*}
\]
Shadowing: tagged DIS

- Explore shadowing through recoil momentum dependence

- Shadowing **enhanced** in tagged DIS compared to inclusive
  - enhancement factor from AGK rules
  - shadowing term drops slower with $p_R$ than IA

- Large FSI effects in diffractive amplitudes ($\sim 40\%$), also at zero spectator momenta due to orthogonality of $np$ state to deuteron

[Guzy, Strikman, Weiss; in preparation]
Nuclear shadowing in exclusive processes

- Can be studied on heavy and light nuclei, large effect
- Gluonic imaging of nuclei $g_A(x, Q^2)$
- Likely gluons belong to more than 1 nucleon
- Shadowing one nucleon at a time in diffractive $J/\psi$ production on light nuclei
- $k$-body FF enter in amplitude $\rightarrow$ nuclear wf

Guzey, Rinaldi et al. 2202.12200
Nuclear imaging

Images of nuclei in terms of quark and gluon dof

- Deeply virtual Compton scattering $\rightarrow$ GPDs
  - coherent: transverse imaging of nuclei
  - incoherent: medium modification of transverse nucleon densities
- Tagged DVCS provides additional control over initial configuration
- Transverse *gluon* structure of light ions ($d$, $^4$He, $^3$He) with exclusive coherent $J/\psi$ production
- Clustering & spin-orbit phenomena in nuclear structure of light nuclei

Fig. credit S. Fucini

$^4$He DVCS
M. Hattawy et al. [CLAS PRL]
Quark density profiles extracted from $^4$He DVCS pseudodata

Roman pot acceptance has clear influence on errors bars

Angular acceptance much more demanding than for $ep$
Nuclear imaging: deuteron tensor polarization

- Tensor polarization in $d$ probes **nuclear effects**
- Little explored in high-energy scattering
- Possible at design EIC (magic energies)
- Inclusive $b_1$ result from HERMES: no conventional nuclear calculation reproduces data
- Unique features: eg access **gluon transversity**, new TMDs & GPDs
- Tagged cross section yields 23 additional structure functions with specific azimuthal dependences [Cosyn, Weiss, in prep.]

$$F_T = T_{LL}[F_{UTLL,T} + F_{UTLL,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UTLL}^{\cos \phi_h} + \varepsilon \cos 2\phi_h F_{UTLL}^{\cos 2\phi_h}]$$

$$+ T_{LL}h \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LTLL}^{\sin \phi_h} + T_{L\perp} [\cdots] + T_{L\perp} h [\cdots]$$

$$+ T_{L\perp} \left[ \cos(2\phi_h - 2\phi_{T\perp}) \left( F_{UTTT,T}^{\cos(2\phi_h - 2\phi_{T\perp})} + \varepsilon F_{UTTT,L}^{\cos(2\phi_h - 2\phi_{T\perp})} \right) \right]$$

$$+ \varepsilon \cos 2\phi_T^{\perp} F_{UTTT}^{\cos 2\phi_T^{\perp}} + \varepsilon \cos(4\phi_h - 2\phi_{T\perp}) F_{UTTT}^{\cos(4\phi_h - 2\phi_{T\perp})}$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \left( \cos(\phi_h - 2\phi_{T\perp}) F_{UTTT}^{\cos(\phi_h - 2\phi_{T\perp})} + \cos(3\phi_h - 2\phi_{T\perp}) F_{UTTT}^{\cos(3\phi_h - 2\phi_{T\perp})} \right) ] + T_{L\perp} h [\cdots]$$

- $T$-odd SF [DSA] are zero in impulse approximation $\rightarrow$ sensitive to FSI
Tagged tensor polarized observable $A_{zz}$ [Frankfurt, Strikman ‘83]

- Tensor analogue of $A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$ is tensor asymmetry $A_{zz} = \frac{\sigma^+ + \sigma^- - 2\sigma^0}{\sigma^+ + \sigma^- + \sigma^0}$

→ no electron polarization required, all 3 deuteron states ($\pm$, 0)

- Tensor polarization is sensitive to unpolarized quark distributions

→ ratio of LF densities remains

$$A_{zz}(\alpha_p, p_T) = -\frac{f_0(k)f_2(k)}{f_0^2(k) + f_2^2(k)} \left(3\cos2\theta_k + 1\right) \quad \alpha_p = \left(1 + \frac{k^3}{\sqrt{m^2 + k^2}}\right); \quad p_T = k_T$$

→ Constraints on deuteron $D$-wave

- Maximal asymmetries (1,-2) for tagged, tiny in inclusive
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 \(\rightarrow\) precision machine
- Coherent phenomena can be explored in light nuclei both in tagged DIS and exclusive measurement
- Quantification of nuclear interaction effects
- Tomography of light nuclei
- Unique observables with polarized deuteron: free neutron spin structure, tensor polarization
- All this requires excellent detection capabilities in far forward region
Tagging: EMC effect

- **Medium modification of nucleon structure embedded in nucleus (EMC effect)**
  - dynamical origin?
  - caused by which momenta/distances in nuclear WF
  - spin-isospin dependence?

- **Tagged EMC effect**
  - recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) away from the on-shell pole
  - EIC: $Q^2$ evolution, gluons, spin dependence!

- **Interplay with final-state interactions!**
  - use $\hat{x} = 0.2$ to constrain FSI
  - constrain medium modification at higher $\hat{x}$