Light-ion physics with EIC: Nuclear structure meets high-energy processes

C. Weiss (Jefferson Lab), Ohio University INPP Seminar, 10 Oct 2023

Light-ion physics with EIC
- Energy, luminosity, polarization, detection
- Objectives and challenges

Spectator nucleon tagging with deuteron
- High-energy process ↔ low-energy structure
- Free neutron structure extraction
- Polarization, NN interactions
- Future: A > 2 systems, EFT methods, …

Coherent processes with light nuclei
- Nuclear GPDs, shadowing dynamics

Physics: Control nuclear configuration during high-energy process… new measurements

Theory: Interplay of high-energy process and low-energy nuclear structure… new methods

Detection: Forward detection of charged and neutral fragments… new solutions

EIC far-forward detectors
Light ions: EIC capabilities

CM energy
\[ \sqrt{s_{ep}} = 20 - 100 (140) \text{ GeV} \]
Lower by \( \sqrt{Z/A} \) for nuclei

High-energy processes: DIS, diffraction

Luminosity
Up to \( \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) (per nucleon)

Rare processes, exceptional configurations

Multivariable final states, polarization observables

Polarized ion beams
Polarized proton and 3He + possibly 7Li, 9Be
Deuteron polarization as facility upgrade

Forward detection of \( p, n, A' \)
Nuclear breakup, spectator tagging
Exclusive and diffractive processes
Coherent nuclear processes \( A \rightarrow A \)
**Light ions: Physics objectives**

**Neutron structure**
- Flavor decomposition of quark distributions and spin
- 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?
  - $\leftrightarrow$ Shadowing and saturation in heavy nuclei

Inclusive measurements

No information on initial-state nuclear configuration

Model effects in all configurations, average with nuclear wave function \( \Psi \ldots \Psi \)

Final-state interactions irrelevant, closure \( \Sigma_X \)

Basic measurements: D, 3He (pol), 4He, ...

Nuclear breakup detection - tagging

Potential information on initial-state nuclear configuration

Study effects in defined configurations, much simpler

Final-state interactions important, influence breakup amplitudes

New opportunities with EIC!
New challenges for detection and theory!
Light ions: Deuteron and spectator tagging

Deuteron as simplest system

Nucleonic wave function simple, well known ($p \sim< 400$ MeV)

Nucleons spin-polarized, some D-wave depolarization

Intrinsic $\Delta$ isobars suppressed by isospin $= 0$
[cf. large $\Delta$ component in $^3$He Bissey, Guzey, Strikman, Thomas 2002]

Spectator nucleon tagging

Identifies active nucleon

Controls configuration through recoil momentum:
spatial size $\rightarrow$ interactions, S/D wave

Typical momenta $\sim$ few $10-100$ MeV

Proton tagging in fixed-target experiments at JLab:
CLAS BONuS 6/12 GeV: $p = 70-150$ MeV
ALERT, HALL A TDIS
Neutron tagging: CLAS12 BAND
Light ions: Spectator tagging with EIC

Spectator moves forward in ion beam direction

Longitudinal momentum controlled by light-cone fraction:

\[ \frac{E_p + p_p^z}{M_D} \approx \frac{1}{2} \left( 1 + \frac{p_p^z}{m} \right). \]

Conserved under boosts

Longitudinal momentum in detector

\[ P_{\parallel p} \approx \frac{P_D}{2} \left( 1 + \frac{p_p^z}{m} \right). \]

Advantages over fixed-target

No target material. Can detect spectators with rest frame momenta down to ~zero

Setup acts as magnetic spectrometer for protons, good acceptance and resolution

Neutron detection with Zero-Degree Calorimeter

Unique opportunity for EIC!

Further information on EIC forward detectors and physics simulations:
EIC Yellow Report 2021 [INSPIRE]
Theory: Tagged DIS cross section

\[
\frac{d\sigma}{dx dQ^2 (d^3 p/E_p)} = \text{[flux]} \left[ F_{Td}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{Ld}(\ldots) + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_p F_{LT,d}(\ldots) + \epsilon \cos(2\phi_p) F_{TT,d}(\ldots) + \text{spin-dep structures} \right]
\]

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: \( p_p^+ = \alpha_p p_d^+ \), \( p_{pT} \)

Related in simple way to rest-frame 3-momentum

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

Special case of target fragmentation: Fracture function

[Trentadue, Veneziano 93; Collins 97]
**QM description**

Nucleon states, nuclear wave function

Nucleons are on mass shell $p^2 = m^2$, energy not conserved in intermediate states

eN scattering subprocess has initial $\neq$ final energy

Energy off-shellness depends on choice of “time” variable

**High-energy limit** $s \rightarrow \infty$

Usual time $x^0$: Energy off-shellness grows with $s$

Light-front time $x^+ = x^0 + x^3$: Off-shellness remains finite!

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**Light-front quantization**

Nucleus described by wave function at fixed light-front time $x^+ \langle pn \mid d \rangle = \Psi(\alpha_p, p_{pT})$

Contains low-energy nuclear structure, just organized in manner suitable for high-energy processes

Enables composite description of high-energy scattering on nucleus:

Separation of nucleus and nucleon structure

Use of on-shell nucleon amplitudes/cross sections, measured in eN scattering

Limited role of non-nucleonic DoF

[Frankfurt, Strikman 80s]
Theory: Light-front quantization

Analogue: Teeing up a golf ball

Light-front quantization:
Low-energy structure aligned with direction of high-energy process

Other quantization schemes:
Low-energy structure not aligned with direction of high-energy process
**Theory: Nuclear light-front wave function**

**LF bound state equation**

Construct NN interaction at fixed LF time $x^+$

Schrödinger ($V$) or Lippmann-Schwinger ($T$) type equations

Technical challenges: Rotational invariance, Fock truncation, $A > 2$


**Approximation constructed from nonrelativistic wave function ($A = 2$)**

Rotationally symmetric representation of LF variables:
\[ k(\alpha_p, p_{pT}) = \text{3-momentum in pn CM frame} \]  
[Terentev 1976]

Match LF and nonrelativistic wave functions:
\[ \Psi_{\text{LF}}(\alpha_p, p_{pT}) = N \Psi_{\text{nonrel}}(k) \]

Approximation safe for $k \lesssim 300$ MeV, possibly larger

Imports knowledge of NN interactions in non-relativistic NMBT

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**Diagram**

- S-wave $k_U$
- D-wave $k_W$

**AV18 deuteron radial wave functions**

$0 \leq k \leq 0.8$ [GeV]
Impulse approximation

Spectator and DIS final state evolve independently

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

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

Final-state interactions

Part of DIS final state interacts with spectator, transfers momentum

Requires theoretical modeling

Strategy

Use measured spectator momentum to control nuclear binding in initial state, interactions in final state

“Select configurations” in nucleus
Tagging: Free neutron structure

Deuteron wave function has pole in unphysical region describing $pn$ configurations of size $\rightarrow \infty$

Universal feature: Bethe-Peierls radius, asymptotic S-wave normalization

At pole nucleons are free, no interactions

Can be reached by analytic continuation in momentum

Light-front: Pole in transverse momentum $p^2_{pT}$

**Extraction procedure**

[Sargsian, Strikman 2005]

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

Divide data by pole term of spectral function

Extrapolate to pole position $p^2_{pT} \rightarrow -a^2_T < 0$

Experimentally challenging: Functions depend strongly on $p_{pT} -$ resolution!
Tagging: Free neutron structure

EIC simulations: p and n tagging, pole extrapolation, uncertainty analysis, validation

Tagged cross section measured with excellent coverage

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

Pole extrapolation realistic for proton spectator, exploratory for neutron sp.

Jentsch, Tu, Weiss, PRC 104, 065205 (2021)

EIC Yellow Report 2021
Tagging: Effective neutron polarization

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

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

\[ = \frac{S_d(\alpha_p, p_{pT})[S]}{S_d(\alpha_p, p_{pT})[U + T]} A_{||,n}(x_n, Q^2) \quad \text{effective neutron polarization, depends on tagged proton momentum} \]

Control effective neutron polarization

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!

Frankfurt, Strikman 1983

Cosyn, Weiss PLB799 (2019) 135035; PRC102 (2020) 065204

EIC simulations: JLab LDRD 2014/15
Tagging: Tensor polarized asymmetry

Maximal tensor polarization can be achieved at $p_{pT} \approx 300$ MeV and $\alpha_p = 1$

$A_{zz, d}(x, Q^2; \alpha_p, p_{pT})$

tagged tensor polarized asymmetry

$$A_{zz, d}(x, Q^2; \alpha_p, p_{pT}) = \frac{d\sigma(+1) + d\sigma(-1) - 2d\sigma(0)}{d\sigma(+1) + d\sigma(-1) + d\sigma(0)}$$

$-2 < A_{zz, d} < 1$

$$A_{zz, d}(x, Q^2; \alpha_p, p_{pT}) = \frac{S_d(\alpha_p, p_{pT})[T_{LL}]}{S_d(\alpha_p, p_{pT})[U]}$$

effective tensor polarization, depends on tagged momentum

$$\approx \frac{1}{\sqrt{UW + \frac{1}{4}W^2}} \times \text{Angular}$$

requires D-wave

Maximize tensor polarized asymmetry

Maximal tensor polarization $A_{zz} = 1$

can be achieved at $p_{pT} \approx 300$ MeV and $\alpha_p = 1$

Much larger tensor asymmetry than in untagged scattering where most events come from nucleon momenta ~ few 10 MeV and D-wave is small

Frankfurt, Strikman 1983
Cosyn, Weiss, in progress
Tagging: Nucleon interactions

Tagged EMC effect

Modification of nuclear parton density observed at $0.3 < x < 0.7$

What NN distances/momenta cause modification?

Use spectator momentum to fix momentum/size of pn configuration

Tagged cross section also affected by final-state interactions.
Needs theoretical estimates → Supplement
Strikman, Weiss 2017

EIC simulations in progress
Jentsch, Tu, Weiss, in progress

Tagging $\Delta\Delta$ configurations

Measure $e + D \rightarrow e' + X' + \pi + N$, reconstruct $\Delta$

Direct demonstration of non-nucleonic degrees of freedom
Tagging: A > 2 nuclei

Will be available at EIC, esp. 3He(pol)

Contain NN pairs with various $I, J, LS$ quantum numbers:
Study nuclear interaction effects in different configurations

Light-front structure more complex:
Angular momentum coupling, LF ↔ nonrelativistic correspondence
Lev 1990s; Salme et al. 2000s

Nuclear breakup processes A > 2

2-body: $e + 3He \rightarrow e' + X + d$

3-body: $e + 3He \rightarrow e' + X + pn, pp$

Breakup more complex: Nuclear interactions in final state, distorted waves, wave function overlap factors

Needs extensive nuclear structure input!

3He: Ciofi, Kaptari, Scopetta e al 2000+
Coherent processes: Nuclear GPDs

Hard exclusive processes

\[ Q^2, W^2 \gg \text{hadronic scale: QCD factorization} \]

Generalized parton distributions \( \langle A' | \hat{\mathcal{O}}_{QCD} | A \rangle \)
Unify concepts of quark/gluon density and form factor

Probe nuclear structure in quark/gluon degrees of freedom

Transverse spatial distribution of quarks/gluons

Compare quark ↔ gluon, charge ↔ matter distributions

Dynamics: Spatial distributions change with \( x \), polarization

Nuclear quark/gluon imaging with EIC

Probe quarks: Deeply-virtual Compton scattering
Probe gluons: \( J/\psi, \phi \) production

Nuclei: D - Spin 1, 3He - Spin 1/2, 4 He - Spin 0
Coherent processes: Nuclear shadowing

Nuclear shadowing

Small-x probe interacts coherently across nucleus

Interference of diffractive scattering from different nucleons along the path

Reduction of nuclear gluon density

Heavy nuclei

Shadowing observed in coherent $J/\psi$ photoproduction in ultraperipheral AA collisions at LHC

Light nuclei

$$\frac{d\sigma}{dt} = 1\text{-body} + 2\text{-body} + \ldots \quad \text{multiple scattering}$$

1-body cross section has diffractive minimum
2-body cross section fills it up

Study onset of coherence and shadowing in coherent processes on light nuclei — new approach

Guzey, Rinaldi, Scopetta, Strikman, Viviani 2022
Coherent processes: EIC simulations

Simulations of coherent DVCS on 4He with ECCE detector
Bylinkin et al 2022

Event generator TOPEG
Dupre, Fucini 2022
Charged particles

Magnetic spectrometer integrated in accelerator optics, several detector subsystems

Transport governed by magnetic rigidity = momentum/charge (for beam and detected particle)

Acceptance depends on $x_L \equiv p_\parallel(particle)/p(beam)$, $\theta = p_\perp/p_\parallel(particle)$ (for given particle)

Neutral particles

Zero-degree calorimeter

Acceptance depends only on angle $\theta$

Complex system, integration is major challenge
EIC far-forward detectors

<table>
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<th>Neutrons</th>
<th>( \theta )</th>
<th>( x_L )</th>
<th>Description</th>
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<th>Protons</th>
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<tr>
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</table>

Spectator tagging

Rigidity(spectator) \( \neq \) Rigidity(beam)

Different subsystems used depending on spectator proton kinematics

Detector resolution \( \rightarrow \) Supplement

Coherent scattering

Rigidity(spectator) \( \approx \) Rigidity(beam)

\[
x_B \approx 1 - x_L \quad \text{longitudinal momentum loss}
\]

Need acceptance at \( x_L \rightarrow 1 \)

Limited by accelerator; can be improved by secondary focus \( \beta_x \approx 0 \) at Roman Pots location

Critical benefits for coherent processes with light ions

Discussed for IR8; possible also at IR6
Summary

Light ion physics most interesting and novel part of EIC science program 😊

Nuclear breakup measurements permit control of nuclear configuration in high-energy process and differential analysis of nuclear effects — new opportunities, new challenges for theory

Light-front formulation of nuclear structure essential for separating low-energy nuclear structure and high-energy process. EFT-based formulation in progress

Unique applications of deuteron tagging at EIC: Free neutron extraction, controlled neutron polarization, large tensor asymmetries, tagged EMC effect, …

Extension of breakup measurements to A > 2 require substantial nuclear structure input: Spectral functions, decay amplitudes for specific final states, final-state interactions

Coherent scattering on light ions: Quark-gluon imaging of nuclei, origin of nuclear shadowing

Synergies with JLab12 + beyond

Rising program — many opportunities, long-term prospects
Supplemental material
Theory: EFT interactions

NN interactions can be generated from Chiral EFT

Scattering amplitude \( T \rightarrow \) Potential \( V \)

Parametric approach: Systematic, controlled uncertainties, organizes N-body forces, current operators

Standard in low-energy nuclear structure
Weinberg; Kaplan et al.; Epelbaum, Meißner et al; Van Kolck et al 1990s/2000s
Schiavilla, Pastore, Piarulli et al 2010s
Machleidt et al. 2000s

Can be extended to light-front NN interactions
Planned: F. Vera, Weiss

Technical questions: Rotational invariance, Fock expansion with chiral counting

Applications: Nuclear pions \( \rightarrow \) antishadowing
Nuclear modifications of PDFs through 2-body operators

Matching with Lattice QCD possible
Vector and tensor polarization

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

3 vector, 5 tensor parameters

Spin observables

U + S + T cross section

$\phi_p$-dependent structures

U + S cross section same as for spin-1/2

Bacchetta et al 2007

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

Time-reversal odd structures: Zero in impulse approximation, serve as tests of FSI
Tagging: Final-state interactions

Part of final state of high-energy process interacts with spectator

Changes spectator momentum distribution, no effect on total cross section (closure)

What final states are produced? How do they interact?
Depends on specifics of high-energy process

**Final-state interactions in DIS at intermediate $x (\gtrsim 0.1)$**

Space-time picture in deuteron rest frame

$\nu \gg$ hadronic scale: Large phase space for hadron production

“Fast” hadrons $E_h = \mathcal{O}(\nu)$ — current fragmentation region:
Formed outside nucleus, interaction with spectator suppressed

“Slow” hadrons $E_h = \mathcal{O}(1 \text{ GeV}) \ll \nu$ — target fragmentation region:
Formed inside nucleus, interact with hadronic cross sections
**Source of FSI in tagged DIS**!

Picture respects QCD factorization of target fragmentation: FSI only modifies soft breakup of target, no long-range rapidity correlations

[Deuteron rest frame view]

[Resonance region: Cosyn, Sargsian Melnitchouk 2011/14]
Tagging: Final-state interactions

Studied distributions of slow hadrons in DIS on nucleon — target fragmentation

Described by light-cone variables
Constrained by light-cone momentum conservation

Used experimental distributions: HERA, EMC, neutrino DIS

Need better data on target fragmentation: JLab12, EIC!

Momentum distribution of slow hadrons in nucleon rest frame: Cone in virtual photon direction

Strikman, Weiss PRC97 (2018) 035209
Tagging: Final-state interactions

FSI calculation

Evaluated scattering of slow hadrons from spectator

QM description: IA + FSI amplitudes, interference

FSI amplitude has imaginary and real part:
Absorption and refraction

Momentum and angular dependence

\[ p_p \lesssim 300 \text{ MeV}: \text{IA} \times \text{FSI} \text{ interference, absorptive, weak angular dependence} \]

\[ p_p \gtrsim 300 \text{ MeV}: |\text{FSI}|^2, \text{refractive, strong angular dependence} \]

Results used in EIC simulations, analysis of JLab12 BAND experiment

FSI angular dependence in deuteron rest frame

Strikman, Weiss PRC97 (2018) 035209
Tagging: 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 $\alpha_{p,n} > 1$, $p_T \sim$ 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
Shadowing: Gluon shadowing in heavy nuclei

Experimental results in coherent J/ψ photoproduction in ultra peripheral AA collisions at LHC CMS and ALICE, compared to leading-twist gluon shadowing and other predictions

Nuclear gluon PDF ratio \( R_g \) in Pb extracted in EPPS21 global analysis

Eskola, Paakkinen, Paukkunen, Salgado 2021

Experimental results in coherent J/ψ photoproduction in ultra peripheral AA collisions at LHC CMS and ALICE, compared to leading-twist gluon shadowing and other predictions
Proton momentum resolution

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

Details depends 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
\( \Delta \alpha_p / \alpha_p \lesssim 5\% \), significantly better for \( \alpha_p \sim 1 \)

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

Summary prepared by A. Jentsch