Light-ion physics at EIC: Low-energy nuclear structure in high-energy processes

C. Weiss, JLab Theory Cake Seminar, 1 March 2023

Context
- Light ions at EIC
- Physics objectives
- Nuclear breakup measurements, esp. deuteron

Theory
- High-energy process ↔ low-energy structure
- Light-front nuclear structure

Applications
- Deuteron + spectator tagging: Free neutron
- Polarized deuteron vector/tensor
- Final-state interactions

Future
- A > 2 systems, EFT methods, …

Based on
JLab LDRD 2014/15 Theory-Experiment:
W. Cosyn, V. Guzey, M. Sargsian, M. Strikman,
D. Higinbotham, Ch. Hyde, P. Nadel-Turonski, K. Park

Theory development: M. Strikman, W. Cosyn

EIC physics/detector simulations, Yellow Report:
A. Jentsch, Zhoudunming Tu
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

Possibly deuteron polarization at special energies

**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 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?
$\leftrightarrow$ Shadowing and saturation in heavy nuclei

**Light ions: Measurements**

**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!
Deuteron as simplest system

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

Neutron spin-polarized, some D-wave depolarization

Intrinsic $\Delta$ isobars suppressed by isospin = 0
[cf. large $\Delta$ component in 3He 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
Spectator tagging with colliding beams

Spectator moves forward in ion beam direction

Longitudinal momentum controlled by light-cone fraction:

Given in deuteron rest frame by

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

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!
Theory: Tagged DIS cross section

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

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]
Theory: Composite picture

QM description

Nucleon states, nuclear wave function

Nucleons are on mass shell $p^2 = m^2$, but intermediate state is off energy-shell — energy different from initial/final state

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!

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: [Frankfurt, Strikman 80s]

Separation of nucleus and nucleon structure

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

Limited role of non-nucleonic DoF
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:
$k(\alpha_p, p_{pT}) = 3$-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
**Impulse approximation**

Spectator and DIS final state evolve independently

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

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

**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

For DIS in scaling regime \( \nu, Q^2 \to \infty \): These approximations are consistent with leading twist factorization of \( \sigma[en, p_{pT}] \), partonic sum rules, etc.
Applications: Free neutron structure

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

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 $p_{pT}^2$

**Extraction procedure**

[Sargsian, Strikman 2005]

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 $p_{pT}^2 \to -a_T^2 < 0$

Experimentally challenging: Functions depend strongly on $p_{pT}$ — resolution!
Applications: 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
Applications: Polarized neutron structure

Neutron polarization in polarized deuteron

\[ S + D \text{ wave, depolarization} \]

Depends on momentum of \( pn \) configuration

Control neutron polarization with tagging

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!

Effects require proper light-front spin structure:
Light-front helicity states, Melosh rotations
[Frankfurt, Strikman 1983]

EIC prospects

Physics simulations: 2014-15 JLab LDRD

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

Cosyn, Weiss, PRC102 (2020) 065204 + in preparation (2023)
Applications: 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 $x$ ($\sim 0.1$)

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]
Applications: 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
Applications: 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

- $p_p \lesssim 300$ MeV: IA x FSI interference, absorptive, weak angular dependence
- $p_p \gtrsim 300$ MeV: $|FSI|^2$, 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
Applications: More deuteron studies with EIC

**Tagged diffractive DIS on deuteron**

Interference of diffractive DIS on p and n

Explore dynamics of nuclear shadowing in A = 2 system

**Tagged EMC effect in deuteron**

Use spectator momentum to fix momentum/size of pn configuration

Explore configuration dependence of EMC effect

**Tagged tensor-polarized DIS**

Use spectator momentum to fix D/S ratio and maximize tensor polarization

Achieve tensor-polarized asymmetry $A_{zz} = O(1)$ as opposed to $\ll 1$ without tagging

Guzey, Strikman, Weiss, in progress

Jentsch, Tu, Weiss, in progress

Cosyn, Weiss, in progress
Future: A > 2 nuclei

Will be available at EIC, esp. $^{3}$He(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 $\leftrightarrow$ nonrelativistic correspondence
Lev 1990s; Salme et al. 2000s

**Nuclear breakup processes A > 2**

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

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

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

Needs extensive nuclear structure input!

$^{3}$He: Ciofi, Kaptari, Scopetta e al 2000+
NN interactions can be generated from ChiralEFT

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
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

Unique applications of deuteron tagging at EIC: Free neutron, tagged EMC effect, diffraction, vector and tensor polarization

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

Prospect of EFT formulation of light-front nuclear structure: Systematic approach

*Rising program — many opportunities, long-term prospects*

*Synergies with JLab12 + beyond*