Nuclear final-state interactions in tagged deuteron DIS at EIC

C. Weiss (JLab), 2018 EIC User Group Meeting, Catholic U., 31-Jul-2018

- Tagged deuteron DIS
  - DIS in controlled nuclear configurations
  - On-shell extrapolation

- Final-state interactions
  - Slow hadrons from nucleon fragmentation
  - Interactions with spectator
  - Momentum and angular dependence

- Extensions
  - Diffraction at $x \ll 0.1$
  - FSI in tagged DIS at $x \to 1$

**EIC simulations:** JLab 2014/15 LDRD
[Webpage]

**Theory:** Continuing effort
**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: Multitude of possible nuclear configurations during high-energy process. Need to “control” configurations!
Light ions: Deuteron, spectator tagging

- Polarized deuteron
  - $pn$ wave function simple, known well
    incl. light-front WF for high-energy procs
  - Neutron spin–polarized
  - Intrinsic $\Delta$ isobars suppressed by Isospin = 0
    $\langle \text{deuteron} \rangle = \langle pn \rangle + \epsilon \langle \Delta \Delta \rangle$

- Spectator nucleon tagging
  - Identifies active nucleon
  - Controls configuration through recoil momentum:
    Spatial size, $S \leftrightarrow D$ wave
  - Tagging in fixed-target experiments
    CLAS6/12 BONUS, recoil momenta $p = 70$-150 MeV

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

- Spectator tagging with colliding beams
  
  Spectator nucleon moves forward with approx. 1/2 beam momentum
  
  Detection with forward detectors integrated in interaction region and beams optics
  LHC $pp/pA/AA$, Tevatron $p\bar{p}$, RHIC $pp$, ultraperipheral $AA$

- Advantages over fixed-target
  
  No target material, $p_p$ (restframe) $\rightarrow$ 0 possible
  
  Potentially full acceptance, good resolution
  
  Can be used with polarized deuteron
  
  Forward neutron detection possible

- Unique physics potential
Tagging: Cross section and observables

\[
\frac{d\sigma}{dx dQ^2 \left( \frac{d^3 p_p}{E_p} \right)} = [\text{flux}] \left[ F_{Td}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{Ld}(\ldots) \right]
\]

\[
+ \sqrt{2\epsilon(1+\epsilon)} \cos \phi_p F_{LT,d}(\ldots) + \epsilon \cos(2\phi_p) F_{TT,d}(\ldots)
\]

+ spin-dependent structures

- Conditional DIS cross section \( e + d \rightarrow e' + X + p \)

Proton recoil momentum \( p_p^+ = E_p + p_p^\perp, \quad p_{pT}, \)

light-front momentum fraction \( p_p^+ = \alpha_p p_d^+ / 2, \)

simply related to \( p_p(\text{restframe}) \)

Conditional structure functions

Special case of semi-inclusive DIS — target fragmentation

QCD factorization Trentadue, Veneziano 93; Collins 97

No assumptions re nuclear structure, \( A = \sum N, \) etc.
Tagging: Theoretical description

- **Light-front quantization**

  High-energy scattering probes nucleus at fixed light-front time \( x^+ = x^0 + x^3 = \text{const.} \)

  Deuteron LF wave function
  \[
  \langle pn|d \rangle = \Psi(\alpha_p, p_{pT})
  \]

  Matching nuclear ↔ nucleonic structure
  Frankfurt, Strikman 80’s

  Low-energy nuclear structure, cf. non-relativistic theory!

- **Composite description**

  Impulse approximation: DIS final state and spectator nucleon evolve independently

  Final-state interactions: Part of DIS final state interacts with spectator, transfers momentum
Tagging: Free neutron structure

- On-shell extrapolation

Proton momentum defines invariant
\[ t - M_N^2 = -2|p_p|^2 + t_{\text{min}} \]
“neutron off-shellness”

Free neutron at pole \( t - M_N^2 = 0 \):
On-shell extrapolation

Eliminates nuclear binding effects and FSI  Sargsian, Strikman 05

- Free neutron structure \( F_{2n} \)

Uncertainty mainly systematic
JLab LDRD: Detailed estimates

- Extension to spin structure \( g_{1n} \)

On-shell extrapolation of asymmetry

D-wave suppressed at \( p_p = 0 \):
Neutron 100% polarized
• Precise measurement of neutron spin structure

Wide kinematic range: Leading ↔ higher twist, nonsinglet ↔ singlet QCD evolution
Parton density fits: Flavor separation $\Delta u \leftrightarrow \Delta d$, gluon spin $\Delta G$
Nonsinglet $g_{1p} - g_{1n}$ and Bjorken sum rule
• DIS final state can interact with spectator
  Changes recoil momentum distributions in tagging
  No effect on total cross section – closure

• Nucleon DIS final state has two components

  “Fast” \( E_h = O(\nu) \)
  hadrons formed outside nucleus
  interact weakly with spectators

  “Slow” \( E_h = O(\mu_{\text{had}}) \sim 1 \text{ GeV} \)
  formed inside nucleus
  interacts with hadronic cross section
  dominant source of FSI, cf. factorization

• FSI effects calculated \( x \sim 0.1–0.5 \)

  Experimental slow-hadron multiplicity distributions
  Hadron-nucleon low-energy scattering amplitudes
  Light-front QM: Deuteron \( pn \) wave function, rescattering process

Strikman, CW, PRC97 (2018) 035209
Cornell, EMC, HERA
Frankfurt, Strikman 81
FSI: Slow hadrons from nucleon fragmentation

- Kinematic variables

\[ \zeta_h, \mathbf{p}_{hT} \quad \text{hadron LC mom} \quad \zeta_h \leftrightarrow x_F \]

Slow hadrons in rest frame have \( \zeta_h \sim 1 \)

\( \zeta_h < 1 - x \) \quad \text{kinematic limit}

- Momentum distribution in rest frame

Cone opening in virtual photon direction

No backward movers if \( h = \text{nucleon} \)

- Experimental data

HERA \( x < 0.01 \): \( x_F \) distns of \( p, n \), scaling

Cornell \( x > 0.1 \): Momentum distns of \( p, \pi \)

Neutrino DIS data \( x \sim 0.1 \)

EIC should measure nucleon fragmentation!

Nucleon structure physics (fracture fnns), input for nuclear FSI
FSI: Momentum and angular dependence

Momentum and angular dependence in rest frame

- $p_p < 300$ MeV \quad $\text{IA} \times \text{FSI}$ interference, absorptive, weak angular dependence
- $p_p > 300$ MeV \quad $|\text{IA}|^2$, refractive, strong angular dependence

Similar dependence observed in quasi-elastic $e + d \rightarrow e' + n + p$
FSI: Effect on on-shell extrapolation

- FSI reduces IA cross section at $|t - M_N^2| \neq 0$ ($\lesssim 0.2 \text{ GeV}^2$)

- FSI vanishes at $t - M_N^2 \to 0$; on-shell extrapolation not affected

FSI: Large $x$

- FSI suppressed for $x \to 1$: Minimum momentum of “slow” hadrons grows

FSI in subasymptotic regime, higher-twist: Cosyn, Sargsian 2010+
• Diffraction in nucleon DIS at $x \ll 0.1$

Nucleon remains intact, recoils with $k \sim$ few 100 MeV (rest frame)

10-15% of events diffractive. Detailed studies at HERA: QCD factorization, diffractive PDFs

• Shadowing in deuteron DIS

Diffraction can happen on neutron or proton: QM interference

Reduction of cross section compared to IA — shadowing. Leading-twist effect.

Frankfurt, Strikman, Guzey 12. Great interest. Hints seen in $J/\psi$ production in UPCs at LHC ALICE.

• Diffraction and shadowing in tagged DIS

Differential studies as function of recoil momentum!

Large FSI effects. Outgoing $pn$ scattering state must be orthogonal to $d$ bound state

Guzey, Strikman, CW 18
FSI: Diffraction at small $x$  

\[ R = \frac{d\sigma(\text{full})}{d\sigma(\text{IA})} \]  as function of neutron $p_{nT}$ for fixed proton $p_{pT}$

- Final-state interactions in diffractive tagged DIS $e + d \rightarrow e' + X + n + p$

Large FSI effects due to orthogonality

Shadowing effects also calculated; can be studied in selected kinematics

Guzey, Strikman, CW, in preparation

Other application: High-$p_T$ deuteron breakup and gluonic structure of small-size $pn$ configuration  

Miller, Sievert, Venugopalan 17
FSI: Applications and extensions

- Tagged EMC effect
  What momenta/distances in $NN$ interactions cause modification of partonic structure?
  Connection with $NN$ short-range correlations?
  FSI theory essential

- Tagged polarized DIS
  FSI effects can be calculated using same techniques
  Spin dependence of slow-hadron distributions unknown – need experimental input

- Breakup of complex nuclei $A > 2$
  Could test isospin dependence and/or universality of bound nucleon structure
  $(A - 1)$ ground state recoil, e.g. 3He (e, e' d) X
  Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014
  Theoretically challenging, cf. experience with quasielastic breakup
  Needs input from 3-body Faddeev calculations for structure and breakup. Bochum-Krakow group.
Summary

- Deuteron and spectator tagging overcome main limiting factor of nuclear DIS: Control of nuclear configurations during high-energy process

  Free neutron structure from on-shell extrapolation
  JLab 2014/15 LDRD Project (C. Weiss et al.) [Webpage]

- FSI between spectator and slow hadrons produced in nucleon fragmentation

  Respects QCD factorization theorem for target fragmentation
  Modifies momentum distribution, preserves total cross section
  Vanishes at on-shell point
  Produces sizable effects for recoil momenta $p_p \sim$ few 100 MeV

- On-shell extrapolation feasible in presence of FSI

- FSI suppressed in tagged DIS at $x \rightarrow 1$

- Future applications: Neutron spin structure, tagged EMC effect, . . .