Hadronization and final-state interactions in nuclear breakup measurements

C. Weiss (JLab), Future of Color Transparency and Hadronization Studies, 7-8 Jun 2021

- Tagged DIS on deuteron
  Applications and theory
  Impulse approximation and final-state interactions

- Final-state interactions
  Hadron distributions in DIS final state
  Hadron formation
  FSI in tagged DIS $x \gtrsim 0.1$

- Extensions
  Polarized tagged DIS
  Exclusive processes
  Breakup of nuclei $A > 2$
Tagged DIS: Applications

- Neutron structure extraction
  Tagged momenta $p \sim$ few 10 MeV
  Free neutron from on-shell extrapolation

- Nuclear interactions: EMC effect, SRCs
  Tagged momenta $p \sim$ few 100 MeV
  Configuration dependence of EMC effect

- Coherent phenomena in QCD at small $x$
  Nuclear shadowing in $A = 2$ system

Basic idea: Use spectator momentum to control nuclear configuration during high-energy process

Tagged inclusive scattering (DIS)
$e + d \rightarrow e' + X + p(n)$

Also exclusive processes, e.g.
$e + d \rightarrow e' + M + p + n$
- **Light-front quantization**

Nuclear structure described at LF time $x^+ = x^0 + x^3$

Off-shellness of nucleon scattering process remains finite in high-energy limit, permits matching with on-shell nucleon amplitudes \textit{Frankfurt, Strikman 1980's}

Deuteron LF wave function $x^+ \langle pn | d \rangle = \Psi(\alpha_p, \mathbf{p}_{pT})$

Low-energy nuclear structure $\leftrightarrow$ non-relativistic theory

- **Composite description**

Impulse approximation IA: DIS final state and spectator nucleon evolve independently

Final-state interactions: Part of DIS final state interacts with spectator, transfers momentum

Use tagged momentum as variable to control nuclear binding, minimize/maximize FSI
Tagged DIS: Neutron structure extraction

- Nuclear binding: Motion, interactions

- Free neutron from on-shell extrapolation

Measure tagged structure function dependence on proton momentum → neutron off-shellness
\[ t - m^2 = -2|p_{pT}| + t_{\text{min}}' \]

Extrapolate to on-shell point \( t - m^2 \to 0 \)

Eliminates nuclear binding effects and FSI
Sargsian, Strikman 2005

EIC simulations
JLab LDRD 2014/15; Jentsch, Tu, CW 2021

- Extension to polarized DIS

Tagged proton momentum controls
S/D ratio, effective neutron polarization
Frankfurt, Strikman 1983; Cosyn, CW 2020

Simulation EIC forward detector IR1 2021
FSI: Final-state interactions

- DIS final state can interact with spectator
  - Changes momentum distributions in tagging
  - No effect on total cross section – closure

Questions

- Hadrons produced in DIS on nucleon: Momentum/angle distributions, spectra, exp data?
- Hadron formation: Times/distances, dependence on kinematics?
- Interaction with spectator: Amplitudes, off-shell effects?

Answers depend on $x$ and $Q^2$ of DIS process

[Similar questions in exclusive processes]

Need input from nuclear transparency measurements!
FSI: Tagged DIS at $x \gtrsim 0.1$

- **Space-time picture in nuclear rest frame**
  Strikman, CW, PRC97 (2018) 035209

  DIS limit $\nu \gg$ hadronic mass scale, $Q^2/\nu$ fixed, large phase space for hadron production

- **Nucleon DIS final state has two components**

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

  "Slow" $E_h = O(\mu_{\text{had}}) \sim 1$ GeV formed inside nucleus interacts with hadronic cross section dominant source of FSI

  ["current" and "target" fragmentation regions]

- **Respects QCD factorization for target fragmentation**
  Trentadue, Veneziano 1993; Collins 1997

  FSI only modifies soft breakup of target, no long-range rapidity correlations
• **Kinematic variables**

\[ \zeta_h, p_{hT} \quad \text{hadron LC momentum} \]

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

\[ \zeta_h < 1 - x \quad \text{kinematic limit} \]

\[ \frac{\zeta_h}{1 - x} \approx -x_F \quad \text{relation to Feynman var} \]

• **Momentum distribution in rest frame**

Constrained by LC momentum conservation

Cone opening in virtual photon direction \( q \)

\( h = \text{nucleon}: \ p_h \text{ always forward, grows for } x \to 1 \)

\( h = \text{pion}: \ p_h \text{ forward or backward} \)
• Measurements of target fragmentation \((x_F < 0)\)
  EMC \(\mu p\) 1986 \(x > 0.02\): \(x_F\) distributions of \(p, \bar{p}, \pi^\pm, K^\pm, \Lambda\)
  HERA \(ep\) 2009/2014 \(x < 0.01\): \(x_F\) distributions of \(p, n\)
  Cornell \(ep\) 1975 \(x > 0.1\): Momentum distributions of \(p, \pi\)

• JLab12 and EIC should measure target fragmentation
  Spin/flavor dependence? Kinematic dependences?
  Interesting nucleon structure physics + necessary input for nuclear FSI!
  Workshop “Target Fragmentation Physics with EIC,” CFNS Stony Brook, 28-30 Sep 2020 [Webpage]
  EIC Yellow Report arXiv:2103.05419
FSI: Strength and momentum dependence

![Graph showing momentum and angle dependence](image)

- Momentum and angle dependence in rest frame
  
  \[ p_p < 300 \text{ MeV} \quad \text{IA} \times \text{FSI interference, absorptive, weak angular dependence} \]
  
  \[ p_p > 300 \text{ MeV} \quad |\text{FSI}|^2, \text{refractive, strong angular dependence} \]

- FSI vanishes at on-shell point \( t - m^2 \to 0 \); extrapolation feasible

- Quantum-mechanical description: Interference, absorption
  Strikman, CW, PRC97 (2018) 035209
FSI: Open questions

• FSI in backward region
  Present treatment includes only FSI from $h = \text{nucleons}$ in DIS final state
  FSI from pions?

  → JLab BAND experiment

• Subasymptotic regime of finite $\nu$ and $Q^2$
  Present treatment assumes DIS limit – large phase space, distinction between fast and slow part of final state
  Connection with resonance region?
  Cosyn, Sargsian, Melnitchouk 2011–

  → JLab 6/12 GeV kinematics
Extensions: Tagging with deuteron

• Tagged DIS with polarized deuteron

  Tagging controls S/D wave ratio
  Frankfurt, Strikman 1983

  Vector-polarized deuteron: Eliminate D-wave depolarization, neutron 100% polarized

  Tensor-polarized deuteron: Realize maximum tensor polarization \([+1, -2]\)

  Spin-dependent effects in FSI?

• Tagged DIS at \(x \ll 0.1\)

  Study configuration dependence of nuclear shadowing

  Diffractive DIS as new source of slow nucleons: Strong FSI, QM treatment
  Guzey, Strikman, CW; in progress

• Tagged exclusive processes

  Meson production or DVCS on neutron

  “Know” forward-going hadron: Simpler FSI calculations, test picture/models
Extensions: Tagging with nuclei $A > 2$

- Potential applications
  - Isospin dependence neutron ↔ proton
  - Universality of bound nucleon structure

- Simplest example: $A=1$ ground state recoil
  - $3\text{He (e, e' d)} X$, including polarization
    Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014; Milner et al. 2018
  - Bound proton ↔ free proton structure

- Nuclear breakup much more complex than $A=2$
  - IA: Wave function overlap, large amplitude factors
  - FSI: Multiple trajectories

Requires new nuclear structure input:
Light-front spectral functions, decay functions, FSI
Workshop “Polarized light ion physics with EIC”, 5-9 Feb 2018, Ghent [Webpage]. Emerging collaboration with low-energy nuclear structure community
• Tagged DIS on deuteron permits control of nuclear configuration during high-energy process and differential treatment of nuclear effects

• Free neutron structure can be extracted model-independently using pole extrapolation, not affected by FSI

• Final-state interactions in tagged DIS at $x \gtrsim 0.1$
  
  Space-time picture of hadron formation and interactions – fast and slow hadrons
  
  Need experimental data on target fragmentation in DIS, $x_F$ distributions
  
  Interactions essentially quantum-mechanical – interference, absorption
  
  FSI effects are $O(1)$ for at $p^{\text{tagged}} \sim$ few 100 MeV
  
  *Can we use tagged DIS to learn about hadronization?*

• Extensions of tagging to $A > 2$ require major theoretical development

• Exciting prospects for programs at JLab12, EIC, J-PARC
Supplementary material
Tagging: Neutron spin structure

- Nuclear binding: Neutron polarization?
  \( S + D \) waves, depolarization
- Control neutron polarization
  Measure tagged spin asymmetries
  D-wave drops out at \( p_{pT} = 0 \):
  Pure S-wave, neutron 100% polarized
  \[ |p_{pT}| \approx 400 \text{ MeV}: \text{D-wave dominates} \]
- Free neutron spin structure
  On-shell extrapolation of asymmetry
- EIC simulations
  Possible with int lumi \( \sim \) few 10 fb\(^{-1}\)

Cosyn, CW, PLB799 (2019) 135035
**FSI: Diffractive DIS at small x**

- **Diffractive scattering:** Nucleon remains intact, recoils with $k \sim$ few 100 MeV (rest frame)

- **Shadowing:** QM interference of diffractive scattering on neutron or proton
  Observed in inclusive nuclear scattering

- **Final-state interactions**

  Low-momentum $pn$ system with $S = 1$, $I = 0$
  
  $pn$ breakup state must be orthogonal to $d$ bound state

  Large distortion, deviations from IA

  Guzey, Strikman, CW; in progress