Tagged Short Range Correlations for Medium to Heavy Ions

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Deep Inelastic Scattering (DIS)

\[ x_B = \frac{Q^2}{2m\omega} \]

\[ Q^2 = 4E_0E \sin^2 \left( \frac{\theta}{2} \right) \]

\[ \omega = E - E' \]

\[
\frac{d\sigma}{d\Omega dE'} = \left( \frac{2\alpha E'}{Q^2} \right)^2 \times \left( \frac{1}{v} F_2 + \frac{2}{m} F_1 \tan^2 \frac{\theta}{2} \right)
\]
The EMC Effect in DIS Scattering

Quark distributions \( (F_2) \) in nucleons bound in nuclei different to distributions in free nucleons, here: \( F_2^C \neq 6 \times F_2^d \)

SLAC data (1994)
EMC slope: 0.32

\[
\frac{2\sigma_C}{12\sigma_d}
\]

\( x \)

Fermi-motion

PRD 49, 4338 (1994)
PRC 65, 015211 (2001)
EMC Effect in Different Nuclei

B. Schmookler et al. (CLAS collaboration), Nature 566, 354 (2019)

\[
\frac{\sigma_A}{A} / \frac{\sigma_D}{2} \quad 12C / D
\]

\[
\frac{\sigma_A}{A} / \frac{\sigma_D}{2} \quad 27Al / D
\]

\[
\frac{\sigma_A}{A} / \frac{\sigma_D}{2} \quad 56Fe / D
\]

\[
\frac{\sigma_A}{A} / \frac{\sigma_D}{2} \quad 208Pb / D
\]
EMC Models

Nucleon Motion
- All nucleons modified slightly
- A few nucleons modified a lot

Medium Modification

Mean Field Modifications

Short Range Correlations (SRC)
Short Range Correlations

- NN pair with
  - large relative momentum > 300 MeV/c
  - small c.m. momentum
  - ~20% of nucleons in nuclei
Short Range Correlations

- NN pair with
  - large relative momentum > 300 MeV/c
  - small c.m momentum
- ~20% of nucleons in nuclei

Knocked-out high-momentum nucleons come with a recoiling partner.

E. Piasetzky et al., PRL 97, 162504 (2006)
Nucleon Momentum Distribution

Mean Field Region
(single-nucleon behavior)

Correlated tail
(2N-SRC behavior)

~1/k^4

80%

20%
Universality of High Momentum Tail

SRCs in Inclusive Scattering

- Quasi-Elastic scattering
- Plateaus due to SRCs

\[ \text{Missing Momentum} = p - q \]

\[ \omega, q \]

B. Schmookler et al. (CLAS collaboration), Nature 566, 354 (2019)

\[ \frac{\sigma_A}{A}/\sigma_D/2 \]
SRCs in Exclusive Scattering

- (e’p) and (e’n) measurements
- Indication of np-dominance for SRC pairs

Duer et al. (CLAS collaboration), Nature 560, 617 (2018)
np-Dominance

- (e’pp) & (e’nп) measurements
- Probability for np pairs about ~18 larger than for pp pairs

We can study SRCs by breaking them.

\[ \text{Missing Momentum} = p - q \]

Leading Proton
Recoil Neutron

\[ \omega, q \]

[Graph showing np fraction and pp fraction for different elements (C, Al, Fe, Pb) with 68% and 95% C.L. ranges.]

Or Hen et al., Science 346, 614 (2014)
To Review: EMC and SRC

EMC Models
- Nucleon Motion
  - Insufficient
- Medium Modification
  - All nucleons modified slightly
  - A few nucleons modified a lot
- Mean Field Modifications
- Short Range Correlations (SRC)

B. Schmookler et al., Nature 566, 354 (2019)

DIS

QE
EMC and SRC Correlation

- Are high-momentum nucleons responsible for the EMC effect?
- Does nucleon modification depend on nucleon momentum?
Tagged DIS on Deuterium

- “Tag“ interacting nucleon by measuring spectator
- How does the bound nucleon structure function depend on nucleon momentum?
- Explaining the EMC effect
Tagged DIS at JLab

Hall B:
CLAS 12 + Backward Angle Neutron Detector (BAND)

- Took first data in Spring 19
- More to come in Fall 19
Two upcoming experiments will test the EMC-SRC connection.

Deep inelastic scattering with a recoiling nucleon:
- Scattered electron jet from struck quark
- Deuterium
- LAD
- 11 GeV e⁻ – SHMS
- HMS
- GEMs
- Spectator proton
- JLab Hall C

Tagged DIS at JLab

Hall B:
CLAS 12 + Backward Angle Neutron Detector (BAND)

- Took first data in Spring 19
- More to come in Fall 19

Hall C:
SHMS/HMS + Large Angle Detector (LAD)

- LAD built, GEMs to be build
- Run in 2021?
DIS Recoil Tagging $d(e,e'N)X$ - Expected Results

$\alpha_s = (E_s - p_{s}^{z})/m_s$

$\rho_{s}^{z}$ [GeV/c] 0.4
Tagged DIS at EIC

- Proton and Neutron tagging
- Polarized deuterons (vector/tensor)
- A > 2 nuclei
- Exclusive processes

- Detecting of recoil particles in forward direction
  - up to low angles, full acceptance
  - over a wide range of momenta
- Possible detection of A-2 system

Jefferson Labs’ LDRD project (2014/15)
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Physics potential of polarized light ions with EIC@JLab```
C. Weiss, D. Higinbotham, P. Nadel-Turonski, W. Cosyn, V. Guzey,
Ch. Hyde, K. Park, M. Sargsian, M. Strikman

Webpage: https://www.jlab.org/theory/tag/
(JL)EIC Overview

- Figure 8 shape design
- Luminosity $10^{33} - 10^{34}$ cm$^{-2}$ s$^{-1}$ (1000x HERA)
- 12 GeV e$^{-}$ 5GeV (lumi max) on 200 GeV p

from M. Diefenthaler HUGS talk 2019
(JL)EIC Ion Detection

- Forward detection of recoil baryons and target fragments
- Detection demanding
  - Need good resolutions
  - Particles down to $p_T = 0$ GeV/c
  - Neutral detection
  - Ion PID
- Detectors
  - Roman pots
  - Zero degree calorimeter
  - Tracking detectors
Tagged SRC at EIC

``Tagged SRCs for medium and heavy ions at the EIC“ (LDRD1912):

• Feasibility of tagged SRCs physics at (JL)EIC
  • Rates at high $x$
  • Resolution at high $x$
  • Beam energies

• Physics Reach

• Simulation and Modeling
  • BeAGLE - eA event generator for EIC
  • Implementing SRCs in BeAGLE
  • EIC detector requirements
  • Reconstruction methods
BeAGLE - Benchmark eA Generator for LEptoproduction


Merger of

- PYTHIA 6 (hard interaction)
- Energy loss of partons: PyQM
- Nuclear environment
  - DPMJET
  - nPDF from EPS09
- Nuclear evaporation by DPMJET3+FLUKA

Short Range Correlations and BeAGLE

- Input to BeAGLE:
  - DIS events based on SRC driven EMC model
  - Quasi-Elastic SRC events from Generalized Contact Formalism (GCF) generator
  - $(A-2)$-system handled by DPMJET3+FLUKA
  - LDRD Project: Focus on $e+C$ and $e+Pb$ simulations
DIS Rate Estimates from $F_2$ Parametrization

$F_2(x,Q^2)$ based on super-fast quark yield parametrization, N. Fomin PRL 105, 212502 (2010)


- Measuring EMC effect at high $Q^2$ easy —> high rate
- SRC ($x > 1$) at high $Q^2$ challenging but non zero rate
Quasielastic Simulation Results

(JL)EIC e+C, 5x50 GeV², QE selection cuts

- Leading, Recoil and Evaporation Nucleons well separated
- Recoil nucleons in challenging 5 - 15 mrad detection region

Plots by Mark Baker

0
0.5
1
1.5
2
2.5
0
0.1
0.2
0.3
0.4
0.5
arb. units

Evaporation Nucleon
Recoil Nucleon
Leading Nucleon

0
5
10
15
20
25
30
35
40
45
50
θ (mr)

Evaporation Nucleon
Recoil Nucleon
Leading Nucleon

Plots by Mark Baker

0
0.5
1
1.5
2
2.5
0
0.1
0.2
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Evaporation Nucleon
Recoil Nucleon
Leading Nucleon

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45
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θ (mr)
Summary and Outlook

- EMC-SRC correlation from electron scattering
- Tagged DIS measurement at JLab to explain EMC effect
  - Measurement of $F_2^p$ with CLAS12 plus BAND
  - Measurement of $F_2^n$ in Hall C with LAD (2021?)
- SRC physics possibilities at (JL)EIC
  - LDRD project
  - First simulation results promising

Near term:
- Continuation of EIC-LDRD project
  - Simulation of DIS event from SRC-EMC model
  - Effects of FSI and intranuclear cascading
  - Resolution requirements
Back up slides
Resolution for $x$ and $Q^2$ in $ep$

- For electron only, worse low $y$ (high-$x$) resolution
- For JB method, low $y$ better but low $Q^2$ worse
- Need a more general approach (e.g. kinematic fitting) for $eA$ in general, and high-$x$ in particular

Electron Only Method

$$Q_e^2 = 4EE' \cos^2(\theta/2)$$

$$= \frac{p_{i,e}^2}{1 - y_e}$$

Jacquet-Blondel Method

$$Q_{JB}^2 = \frac{(\sum_i p_{x,i})^2 + (\sum_i p_{y,i})^2}{1 - y_{JB}}$$

$$= \frac{p_{i,h}^2}{1 - y_{JB}}$$
**EIC Detector**

**What do we measure?**
- Lepton scattering on a proton
- Current jet (or hadron)
- Target fragments

**Inclusive DIS:**
- Only electron is detected

**Semi-Inclusive DIS (SIDIS):**
- Electron and current jet (hadron) are detected.

**Exclusive reactions:**
- All particles are detected

**Scattered electron**

**Current jet (or hadron)**

**Target fragments**
QE Simulation Results

Neutrons from e+C JLEIC 5x50 $Q^2 > 3$ GeV$^2$ $x>1.2$

Protons from e+C JLEIC 5x50 $Q^2 > 3$ GeV$^2$ $x>1.2$

Evaporation Neutron

Recoil Neutron

Leading Neutron

Evaporation Neutron

Recoil Neutron

Leading Neutron

Evaporation Neutron

Recoil Neutron

Leading Neutron

Evaporation Neutron

Recoil Neutron

Leading Neutron

Evaporation Proton

Recoil Proton

Leading Proton

Evaporation Proton

Recoil Proton

Leading Proton

Evaporation Proton

Recoil Proton

Leading Proton
F₂ from N. Fomin Paper and Reimplementation

N. Fomin PRL 105, 212502 (2010)

Hauenstein  | 08/24/2019
FSI in Tagged DIS

DEEPS showed little FSI at back angles.

Klimenko et al., PRC 73 035212 (2006)
Theories

Theories identify virtuality as the key to producing EMC-like modification.

- **Binding**
  - Free
  - Bound

- **Rescaling**
  - Free

- **Point-like Configuration Suppression**
  - Free
  - Free
  - Bound

Mathematical expression:

\[ A - 1 \]