Forward Tagging in an Electron-Ion Collider

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recent EIC white papers:

Why a Polarized Electron-Ion Collider?

- Longitudinal & Transverse Ion polarization at IP
  - No intense transverse B-field at IP to disrupt electron beam
- Forward boost (incident ion species $P(A) = ZP_0$)
  - Target fragmentation region is boosted/easier to detect
    - Rapidity gap events can be identified
  - Spectator fragments are boosted forward
    - Incident ion species total momentum $P(A) = ZP_0$
    - Spectator fragment momenta $P(A') \approx A'(Z/A)P_0$
      - Spectator nucleon $p' = ZP_0/A$
    - Tag the initial momentum of the struck nucleon in DIS, SIDIS, DVES reactions on light nuclei.
    - Reconstruct the full nuclear final state in DIS on nuclei
JLab LDRD-2014 Project on Spectator Tagging in Polarized Light Ions

- JLab:
  - Ch. Weiss, D. Higinbotham, W. Melnitchouk, P. Nadel-Turonski,
- Old Dominion U.
  - Ch. Hyde, KJ Park, S. Kuhn
- Florida Int’l U.
  - M. Sargsian
- St. Petersburg State U.
  - V. Guzey
- Spectator Tagging on polarized D, $^3$He
  - $D(e,e'N_S)X$
  - SIDIS $D(e,e'N_S h) X'$
  - DVES $D(e,e'N_S M N_{active})$
Neutron structure through spectator tagging

- Scattering on *bound neutrons*
  - Fermi motion,
  - NN correlations
  - Depolarization
- Solution is *Spectator Tagging*
  - *Fixed target:*
    - Low-momentum spectators
    - Thick Targets
    - Electron-Ion Collider
    - Spectator fragments are ultra-forward.
- The MEIC is designed from the outset to tag spectators, and other nuclear fragments.
Nuclear Spectral Functions

- $^2$H and $^3$He
  - ‘Neutron’ targets
- Mean field $\approx 80$
- Correlations
  - EMC Effect
  - Modified quark-gluon structure

![Graph showing momentum distributions of various nuclei](M Alvioli, et al., PRC 87 (2013) 034603)
The EMC Effect and NN Correlations


- Recent $^{12}$C JLab ‘EMC’ data
  J. Seely PRL 103 (2009) 202301

- N. Fomin et al, PRL 108 (2012) 092502

**FIG. 2:** Per-nucleon cross section ratios vs $x$ at $\theta_c = 18^\circ$. 
**ePHENIX (fsPHENIX) Detector Concept**

TK Hemmick, Future Trends in High Energy Nuclear Collisions, Beijing 2013

- **fsPHENIX definition:**
  - sPHENIX with hadron endcap
  - Adds GEM-tracking, RICH, Aerogel, addn’l ecal & hcal.
  - Leaves sPHENIX barrel unchanged.

- **ePHENIX definition:**
  - fsPHENIX with electron endcap
  - Removes silicon tracking
  - Adds crystal emcal, TPC, DIRC.

**Discussing ePHENIX covers all of fsPHENIX**
eRHIC: high-luminosity IR

- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb₃Sn focusing magnets
- Arranged free-field electron pass through the hadron quad-triplet
- Integration with the detector: efficient separation and registration of low angle collision products

eRHIC - High-lumi IR with $\beta^*=5$ cm, $l^*=4.5$ m $\rightarrow 10^{34}$ cm⁻² s⁻¹

DVCS: $Q^2>1$ GeV, $0.01<y<0.95$, $E_\gamma>1$ GeV

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EIC – accelerator layout at JLab

- The MEIC has the same circumference as CEBAF or about 1/3 of RHIC
The full-acceptance detector concept

Forward hadron detection in three stages:

1. Endcap with 50 mrad crossing angle
2. Forward 2 T•m dipole covering angles up to a few degrees
3. Far-forward, up to 1° (neutrals) and 0.5° charged particles
Far-Forward hadron detection

- **Neutron** detection in a 20 mrad cone down to $0^\circ$

-DREAM HCAL: $\sigma(\theta) = 1\text{cm}/40\text{m}=2.5\cdot10^{-4}$ rad
$\sigma(E)/E = 30\%(1\text{GeV}/E)^{1/2}$

- Excellent acceptance for all ion fragments

- **Recoil proton** acceptance:
  - $0 < \theta < 10$ mrad for $|P' - P_0| > (0.05\%)$ $P_0$
  - $2 < \theta < 10$ mrad for all $P'$
  - $0.3 \ P_0 < (Z/Z') \ P_0 < \infty$

- Momentum resolution $< 3\cdot10^{-4}$

*Beam energy spread*
The Deuteron

Deuteron Momentum Density

Rest Frame

Lightcone: \( p_\perp, \alpha = \frac{E_N + p_N}{E_D + p_D} \)

Momentum Density (GeV/c)^3
Proton Spectator Tagging in the Deuteron

- **MEIC:**
  - Polarized DIS, SIDIS, DVES... on bound Neutron
  - Each contour is $3\sqrt{10}$
- **eRHIC:**
  - Unpolarized

Deuteron Momentum Density (GeV/c)$^{-3}$

$D(e,e'p_s) \times 1-\sigma$ resolution, $P_d=100$ GeV/c

$P_{\perp}$ (GeV/c)

$\alpha=p^+/P^+$

MEIC Resolution
Neutron Spectator Tagging in the Deuteron

- **MEIC**
  - Polarized DIS, SIDIS, DVES... on bound proton
- **eRHIC**
  - unpolarized
In this section the momentum distributions of several nuclei are presented and the values of the quantity \( \sigma \) are adopted. In the next section the momentum distributions of several nuclei are presented and the values of the quantity \( \sigma \) are adopted.

The full momentum distributions are shown in Figs. 16–20, corresponding to various two-nucleon interactions, will be presented. As already stated in Sec. III, the proton momentum distribution is given by

\[
|\langle k | p \rangle| = \frac{1}{\sqrt{A}} n_A(k) \equiv \frac{1}{\sqrt{A}} n_3(k)
\]

where \( n_A(k) \) are

- Active Neutron \( \Rightarrow \)
- Tagging of the two spectator protons
- Active Proton \( \Rightarrow \)
- Tagging of spectator proton and neutron.
- Tag spectator deuteron
- Polarized \( ^3\)He:
  - Neutron: +86\% polarized.
  - Each Proton:
    - –2.8\% polarized.

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Nuclear Tagging

• A hot nucleus decays by emitting neutrons, protons of ~10 MeV, or $p_{\text{perp}} \leq 140$ MeV/c
• Incident nucleus $P_A = Z \cdot 100$ GeV/c
  • per nucleon $p = (Z/A) \cdot 100$ GeV/c $\Rightarrow 50$—$40$ GeV/c
  • Evaporation neutrons $\theta \sim 0.14/40 = 3.5$ mr
• Forward baryon multiplicity as a tag on centrality in DIS?
Intrinsic Charm

- $\gamma^* + p \rightarrow X + \Lambda_c$ ‘Spectator $\Lambda_c$’
  - $\Lambda_c \rightarrow pK^0$ 2.3%
- For 100 GeV/c incident protons
  - Spectator $\Lambda_c$ momentum $\sim 60$ GeV/c
  - 50% of $\Lambda_c$ decay protons are $\leq 1.5^\circ$
  - 75% of $\Lambda_c$ decay protons are $\leq 2.4^\circ$
  - Tagging in Forward region after small (6 mr bend) dipole

50 mr crossing angle in ion beam
A high-luminosity Electron-Ion Collider

• Unprecedented capabilities to study the QCD structure of matter
• Polarized Light Ions:
  ▪ Precision study of neutron structure
    ◆ Spectator proton tagging
  ▪ Quark-gluon structure of nuclear binding
    ◆ Bound proton structure via neutron tagging
    ◆ DIS, SIDIS, DVES processes identified in mean-field and NN-correlations regions
• Target fragmentation region
  ▪ Heavy Quarks
• Heavy Nuclei
  ▪ Tag the full nuclear final state ➔ DIS vertex tagging?
Back-up Slides
How to Tell the Spectator Nucleons from the Active Nucleon?

• DIS, SIDIS
  • Target fragmentation produces a forward nucleon
  • Fragmentation increases $p_\perp$, decreases $p_\parallel$

• DVES:
  • $p_z' \approx p_z (1-x_B) \Rightarrow p'^+/P^+ \approx \alpha - x_B$
  • $-t = -\Delta^2 \approx (x_B^2 M^2 + \Delta_\perp^2)/(1-x_B)$
  • D, $^3$He, Momentum densities fall by $\sim 1/1000$ for $x_B > 0.1$, or
    $\Delta_\perp = p_\perp' > 300$ MeV/c $\Rightarrow -t > 0.1$ GeV$^2$
    Antisymmetrization < 3%
  • At smaller $x_B$ and smaller $p_\perp'$, sum over all nucleons as active or spectator, w/ anti-symmetrization
Ultra-forward charged-hadron acceptance

Red: Detection before ion quadrupoles
Blue: Detection after ion quadrupoles

Forward acceptance vs. magnetic rigidity

50 mr crossing angle in ion beam

Tagged d beam: $\Delta p/p = -0.5$
Tagged $^3$He beam: $\Delta p/p = +0.33$
eRHIC: design luminosity

\[ L, \text{ cm}^{-2} \text{ sec}^{-1} \]

\[ E_e, \text{ GeV} \]

\[ E_p, \text{ GeV} \]
**eRHIC: design luminosity**

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>$^2\text{He}^3$</th>
<th>$^{79}\text{Au}^{197}$</th>
<th>$^{92}\text{U}^{238}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>20</td>
<td>250</td>
<td>167</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>CM energy, GeV</strong></td>
<td>100</td>
<td>82</td>
<td>63</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>Number of bunches/distance between bunches</td>
<td>107 nsec</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity (nucleons), $10^{11}$</td>
<td>0.36</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>5.8</td>
<td>64</td>
<td>60</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td>Beam current, mA</td>
<td>50</td>
<td>556</td>
<td>556</td>
<td>335</td>
<td>338</td>
</tr>
<tr>
<td>Normalized emittance of hadrons, 95%, mm mrad</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Normalized emittance of electrons, rms, mm mrad</td>
<td>16</td>
<td>24</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Polarization, %</td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>rms bunch length, cm</td>
<td>0.2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\beta^*$, cm</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Luminosity per nucleon, $\times 10^{34}$ cm$^{-2}$s$^{-1}$</strong></td>
<td>2.7</td>
<td>2.7</td>
<td>1.6</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

- Hourglass the pinch effects are included. Space charge effects are compensated.
- Energy of electrons can be selected at any desirable value at or below 30 GeV.
- The luminosity does not depend on the electron beam energy below or at 20 GeV.
- The luminosity falls as $E_e^{-4}$ at energies above 20 GeV.
- The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$.
## Parameters for Full Acceptance Interaction Point

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>MHz</td>
<td>750</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
</tr>
<tr>
<td>Beam Current</td>
<td>A</td>
<td>0.5</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
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<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
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<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
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<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
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<tr>
<td>Horizontal $\beta^*$</td>
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<td>10</td>
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<td>Vertical $\beta^*$</td>
<td>cm</td>
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<tr>
<td>Vertical beam-beam tune shift</td>
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<td>0.014</td>
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<tr>
<td>Laslett tune shift</td>
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<td>0.06</td>
</tr>
<tr>
<td>Distance from IP to 1st FF quad</td>
<td>m</td>
<td>7</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Recoil baryon detection:
Small beam size ($\beta$) and large dispersion at the secondary focal point give superb resolution and acceptance at very small angles.

Excellent $t$-coverage for all kinematics!
Spectator tagging in a collider

- $P_D = 100 \text{ GeV}/c$ deuteron
  - $p_p \approx (P_D/2)(1+\alpha) + p_\perp f$
    - $\alpha < 50 \text{ MeV}/1\text{GeV}$, $\theta_s = p_\perp/(P_D/2) \leq 1 \text{ mrad}$
  - $p_n \approx (P_D/2)(1-\alpha) - p_\perp$
    - Measure $\theta_n \approx p_\perp/(P_D/2)$ accurately in Forward Hadronic Calorimeter (integrate over $\alpha$).
      $\delta \theta_n \approx (1 \text{ cm})/(40 \text{ m}) = 0.25 \text{ mrad}$

- $P(^4\text{He}) = 200 \text{ GeV}/c = ZP_0$
  - Magnetic rigidity $K(^4\text{He}) = P/(ZB) = (100 \text{ GeV}/c)/B = K_0$
  - $P(\text{Spectator} \, ^3\text{He}) \approx (3/4)P(^3\text{He}) \Rightarrow K(^3\text{He}) = (3/4) \, K_0$
  - $P(\text{Spectator} \, ^3\text{H}) \approx (3/4)P(^3\text{H}) \Rightarrow K(^3\text{H}) = (3/2) \, K_0 > K_0$
Nuclear Spectral Functions

- C. Ciofi degli Atti, S. Simula
  PRC 53 (1996)