Polarized deuterium physics with EIC
C. Weiss (JLab), Tensor Polarized Solid Target Workshop, JLab, 11–Mar–14

- Electron-Ion Collider overview
  - Design specifications
  - eA physics objectives
  - Why deuterium

- Polarized deuterium with EIC
  - Inclusive $eD \rightarrow e' + X$
  - Spectator tagging $eD \rightarrow e' + p/n + X$: Neutron structure, bound nucleon
  - Multiple scattering: Shadowing, tensor polarization

- Accelerator and detector designs
  - Forward detection with JLab MEIC

- Precision measurements using $eD$ with forward tagging

Kinematic reach in $x, Q^2$ for sea quarks, gluons, coherence
Ion polarization $L, T$, tensor
Forward detection of $p, n, D$
EIC: Specifications

- Energy–luminosity frontier
  - First $eA$ collider!
  - First polarized $ep/eA$ collider!

- Design specifications
  - CM energy 20-70 GeV/nucleon, higher energies in 2nd stage
  - Luminosity $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ over wide range of energies
  - Proton and ion polarization
    - Polarized deuterium with JLab design only!
  - Detection of forward $p, n$, nuclear fragments

- $ep$ physics program
  - Sea quark spin/flavor, gluon $\Delta g$
  - Spatial distributions, orbital motion
  - “3D nucleon structure” 2012 White Paper, reviews

Convergence in design goals
Differences in technological challenges
EIC: $eA$ physics goals

**Neutron structure:** Flavor decomposition of quark spin, $\Delta g$ ←

**Bound nucleon:** Modification of quark/gluon structure by nuclear medium ←

**Collective quark/gluon fields:** Shadowing, diffraction, high densities ←

**Nucleus as filter:** Color transparency, parton propagation, hadronization

**Importance of deuterium**

Simple structure: Wave function (incl. light-front), polarization

Manageable multiple scattering: Final-state interactions, coherence

Effective control through spectator tagging

Tensor polarization as $N = 2$ observable
Deuterium: Inclusive scattering

- **Inclusive** $eD \rightarrow e' + X$

  $eD + ep$: Spin/flavor of sea quarks at $x \sim 10^{-1}$–$10^{-3}$

  $eD$ alone: $\Delta G$ from isoscalar $Q^2$ evolution

  Excellent statistics, accuracy limited by systematics, e.g. polarimetry

- Theoretical uncertainty in nucleon structure extraction

  Final–state interactions: Debris hits downstream nucleon

  Shadowing: Coherent scattering from both nucleons, $x < 10^{-1}$

- Much better control with spectator tagging
Deuterium: Spectator tagging

- Tagged DIS $eD \rightarrow p/n + X$
  - Control quantum state of active nucleon
  - Measure recoil LC momentum $\alpha_R, p_{RT}$

- Impulse approximation
  - $t = (p_R - p_D)^2$
  - $d\sigma / dx \, dQ^2 \, (d\alpha_R / \alpha_R) \, d^2p_{TR} = \text{factor}$
  - $\times |\psi_{LC}^{D}(\alpha_R, p_{TR})|^2 \, F_{2N}[x/(2 - \alpha_R), Q^2]$  
    - Deuteron LCWF  
    - Nucleon SF

- On-shell extrapolation $t \rightarrow M_N^2$
  - Free nucleon structure at pole
  - Pole value not affected by FSI
  - Sargsian, Strikman 05: "No-loop theorem"

- Model-independent method!
Deuterium: Spectator tagging with MEIC

- Extract free nucleon structure
  Forward detection down to $p_{TR} \sim 0$
  uses most of momentum distribution

  Excellent momentum resolution
  $\Delta \alpha_R = O(10^{-4})$, $\Delta p_{TR} \sim 15$ MeV

  Accuracy limited by intrinsic momentum spread in ion beam

  On-shell extrapolation appears feasible, MC simulations in progress
  JLab LDRD Project “Polarized light ions with EIC@JLab”

- Many applications
  Neutron structure $F_2^n$ at $x < 10^{-1}$, especially nonsinglet $(p - n) \sim (u - d)$
  Bound proton through neutron tagging, comparison with free proton structure
  Spin structure function $g_1^n$ for polarized PDF fits

K. Park, based on cross section model by M. Sargsian
Deuterium: Coherent effects

- Shadowing in inclusive DIS $x \ll 10^{-1}$
  - Diffractive scattering on single nucleon
    - Leading-twist effect! Seen at HERA
  - Interference between scattering on nucleons 1 and 2
  - Nuclear effect calculable in terms of nucleon’s diffractive structure functions
    - Gribov 70’s. Frankfurt, Guzey, Strikman 02+
  - Determines approach to “saturation”

- Shadowing in tagged DIS
  - New experimental tests through recoil momentum dependence
    - Guzey, Strikman, CW; in progress
  - Clean coherent effect with $N = 2$
  - Extend to polarized DIS!
    - Tensor polarization also $N = 2 \rightarrow$ Talk Kalantarians

- Coherent scattering $eD \rightarrow e + M + D$
  - Exclusive meson production, DVCS, nuclear GPDs
Facilities: EIC accelerator designs

- **BNL linac–ring design eRHIC**
  RHIC proton/ion beam up to 325 GeV
  5–20 (30) GeV electron linac in tunnel **staged**
  Luminosity \( \sim 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) over wide range
  Re-use RHIC detectors? **PHENIX, STAR**

- **JLab ring–ring design MEIC/ELIC**
  11 GeV CEBAF as injector **continued fixed-target op**
  Medium–energy: 1 km ring, 3–11 on 60/96 GeV
  High–energy: 2.5 km ring, 3–11 on 250 GeV
  Luminosity \( \sim 10^{34} \) over wide range
  Figure–8 for polarization transport **Up to four IPs**
  Polarized deuterium beam \( \leftarrow \)

- **Related proposals**
  CERN LHeC: 20–150 GeV on 7 TeV \( ep \) unpol
  Ring–ring and linac–ring discussed, \( L \sim 10^{33} \)
  EIC@China project in Lanzhou
  Design targets similar to JLab MEIC

Convergence in design parameters, “staging.”
Different technological challenges!
Facilities: MEIC full–acceptance detector

Design goals

- Detection/identification of complete final state
- Recoil $p_T$ resolution $\ll$ Fermi momentum
- Low–$Q^2$ electron tagger for photoproduction
Facilities: MEIC far-forward detection

- Good acceptance for all ion fragments – rigidity different from beam
  
  Large magnet apertures (small gradients at a fixed maximum peak field)
  
  Roman pots not needed for spectators and high-$p_T$ fragments

- Good acceptance for low-$p_T$ recoils – rigidity similar to beam
  
  Small beam size at detection point (downstream focus, efficient cooling)
  
  Large dispersion (generated after the IP, $D = D' = 0$ at the IP)
  
  With 10σ beam size cut, the low-$p_T$ recoil proton acceptance is
  
  Energy up to 99.5% of the beam for all angles
  
  Angular down to 2 mrad for all energies

- Good momentum and angular resolution
  
  Should be limited only by initial state (beam)
  
  Longitudinal $dp/p$: $4 \times 10^{-4}$
  
  Angular in $\theta$, for all $\phi$: 0.2 mrad
  
  $p_{TR} \sim 15 \text{ MeV}/c$ resolution for tagged 50 GeV/A deuterium beam

  Long, instrumented drift space (no apertures, magnets, etc.)

- Sufficient beam line separation ($\sim 1 \text{ m}$)
LDRD project: Polarized light ions

D. Higinbotham, W. Melnitchouk, P. Nadel–Turonski, K. Park, C. Weiss (JLab), Ch. Hyde (ODU), M. Sargsian (FIU), V. Guzey (PNPI), with collaborators W. Cosyn (Ghent), S. Kuhn (ODU), M. Strikman (PSU), Zh. Zhao (JLab)

Objectives
Develop physics models for DIS processes on polarized light ions (D, 3He) with tagged nucleons
Implement in MC generator with schematic modeling of EIC beam/detector characteristics
Simulate processes and demonstrate feasibility of physics extraction

• Project started Dec 2013

• 50% FTE experimental physics postdoc (shared with ODU): Kijun Park
  Senior theory collaborators as long-term visitors in Summer 2014

• Cross section model for unpolarized $D$ available (Sargsian)
  Shadowing model being developed (Guzey)
  MC generator development in progress (Park, Higinbotham, Hyde, Nadel-Turonski)
  Simulations of extraction of unpolarized $F_2^p, F_2^n$ with forward tagging
  Next steps: Final-state interactions, polarized $g_1^p, g_1^n$, DVCS

• Open for collaboration!
  Physics models and generators to be made available
  Extension to other processes of interest possible
Summary

• Deuteron as target of choice for precision nuclear physics
  Free neutron structure from on-shell extrapolation
  Polarization, incl. tensor
  Coherent effects at $N = 2$

• JLab MEIC offers unique opportunities for $eD$ measurements
  Kinematic reach for sea quarks, gluons, coherence
  Polarization, incl. tensor
  Forward tagging of $p, n, D$

  Qualitative advances!

• Natural extension of JLab 6/12 GeV nuclear physics program
  Unique expertise! Much to contribute. . .