Next-generation spin physics measurements with polarized deuteron and spectator tagging

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in collaboration with
Ch. Weiss, JLab LDRD project on spectator tagging

Why focus on light ions at an EIC?

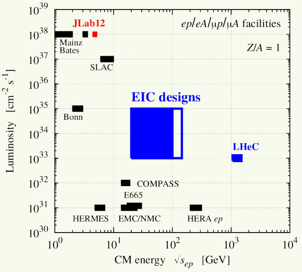
- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - coherent phenomena

- Light ions have unique features
  - polarized beams
  - breakup measurements & tagging
  - first principle theoretical calculations of initial state

- Intersection of two communities
  - high-energy scattering
  - low-energy nuclear structure

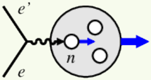
Use of light ions for high-energy scattering and QCD studies remains largely unexplored

EIC design characteristics (for light ions)



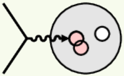
- CM energy $\sqrt{s_{eA}} = \sqrt{Z/A}\ 20 - 100\text{GeV}$
  DIS at $x \sim 10^{-3} - 10^{-1}$, $Q^2 \leq 100\text{GeV}^2$
- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables
- Polarized light ions
  - ^{3}He, other @ eRHIC
  - d, ^{3}He, other @ JLEIC (figure 8)
  - spin structure, polarized EMC, tensor pol, ...
- Forward detection of target beam remnants
  - diffractive and exclusive processes
  - coherent nuclear scattering
  - nuclear breakup and tagging
  - forward detectors integrated in designs

Light ions at EIC: physics objectives



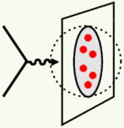
Neutron structure

- flavor decomposition of quark PDFs/GPDs/TMDs
- flavor structure of the nucleon sea
- singlet vs non-singlet QCD evolution, leading/higher-twist effects



Nucleon interactions in QCD

- medium modification of quark/gluon structure
- QCD origin of short-range nuclear force
- nuclear gluons
- coherence and saturation

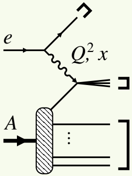


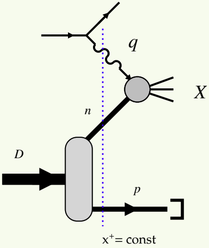
Imaging nuclear bound states

- imaging of quark-gluon degrees of freedom in nuclei through GPDs
- clustering in nuclei

Need to control nuclear configurations that play a role in these processes

Theory: high-energy scattering with nuclei



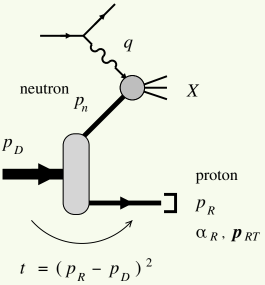


- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$
- Scales can be separated using methods of light-front quantization and QCD factorization
- Tools for high-energy scattering known from *ep*
- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron
  - still **low-energy** nuclear physics, just formulated differently

`Frankfurt, Strikman '80s`
`Kondratyuk, Strikman, NPA '84`

Neutron structure with tagging

- EIC will measure **inclusive** DIS on light nuclei [d, ^{3}He, ^{3}H(?)]
  - Simple, no FSI effects
  - **Uncertainties** limited by nuclear structure effects (binding, Fermi motion, non-nucleonic dof)
- Proton tagging offers a way of controlling the nuclear configuration



- Advantages for the deuteron
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable
- Allows to extract **free** neutron structure with pole extrapolation
  - Eliminates nuclear binding and FSI effects `[Sargsian,Strikman PLB '05]`
- Suited for colliders: no target material ($p_p \rightarrow 0$), forward detection, polarization.
  fixed target CLAS BONuS limited to recoil momenta ~ 70 MeV

Theoretical Formalism

- General expression of SIDIS for a polarized spin 1 target
  - Tagged spectator DIS is SIDIS in the target fragmentation region

$$\vec{e} + \vec{\vec{T}} \rightarrow e' + X + h$$

- Dynamical model to express structure functions of the reaction
  - First step: impulse approximation (IA) model
  - Results for longitudinal spin asymmetries
  - FSI corrections (unpolarized `Strikman, Weiss PRC '18`)

- Light-front structure of the deuteron
  - Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**

Polarized spin 1 particle

- Spin state described by a 3*3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon–target axis

$$W_D^{\mu\nu} = Tr[\rho_{\lambda\lambda'} W^{\mu\nu}(\lambda'\lambda)]$$

- Characterized by **3 vector** and **5 tensor** parameters

$$S^\mu = \langle \hat{W}^\mu \rangle , \qquad T^{\mu\nu} = \frac{1}{2}\sqrt{\frac{2}{3}}\langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3}\left(g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2}\right)\rangle$$

- Split in longitudinal and transverse components

$$\rho_{\lambda\lambda'} = \frac{1}{3}\begin{bmatrix} 1 + \frac{3}{2}S_L + \sqrt{\frac{3}{2}}T_{LL} & \frac{3}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} - \sqrt{3}T_{LT}e^{-i(\phi_h-\phi_{T_L})} & \sqrt{\frac{3}{2}}T_{TT}e^{-i(2\phi_h-2\phi_{T_T})} \\ \frac{3}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} - \sqrt{3}T_{LT}e^{i(\phi_h-\phi_{T_L})} & 1-\sqrt{6}T_{LL} & \frac{3}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} + \sqrt{3}T_{LT}e^{-i(\phi_h-\phi_{T_L})} \\ \sqrt{\frac{3}{2}}T_{TT}e^{i(2\phi_h-2\phi_{T_T})} & \frac{3}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} + \sqrt{3}T_{LT}e^{i(\phi_h-\phi_{T_L})} & 1 - \frac{3}{2}S_L + \sqrt{\frac{3}{2}}T_{LL} \end{bmatrix}.$$

- Can be formulated in **covariant** manner $\rightarrow \rho^{\mu\nu} = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'}\epsilon^{*\mu}(\lambda')\epsilon^\nu(\lambda)$

Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ($qW = Wq = 0$)
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2\alpha^2}{Q^4(1-\epsilon)}(F_U + F_S + F_T)\, d\Gamma_{P_h},$$

  - U + S part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$\begin{aligned}
F_S = {} & S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon\sin 2\phi_h F_{US_L}^{\sin 2\phi_h}\right] \\
& + S_L h\left[\sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LS_L}^{\cos\phi_h}\right] \\
& + S_\perp\left[\sin(\phi_h-\phi_S)\left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)}\right) + \epsilon\sin(\phi_h+\phi_S) F_{US_T}^{\sin(\phi_h+\phi_S)}\right. \\
& \left. +\epsilon\sin(3\phi_h-\phi_S) F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h-\phi_S) F_{US_T}^{\sin(2\phi_h-\phi_S)}\right)\right] \\
& + S_\perp h\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S) F_{LS_T}^{\cos(\phi_h-\phi_S)} + \right. \\
& \left. \sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h-\phi_S) F_{LS_T}^{\cos(2\phi_h-\phi_S)}\right)\right],
\end{aligned}$$

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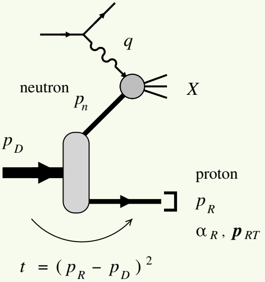
$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T) \, d\Gamma_{P_h} ,$$

  - 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive (b_{1-4}) [Hoodbhoy, Jaffe, Manohar PLB'88]

$$\begin{aligned}
F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{L\perp} [\cdots] + T_{L\perp} h [\cdots] \\
& + T_{\perp\perp} \Big[\cos(2\phi_h - 2\phi_{T_\perp}) \Big(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_\perp})} \Big) \\
& + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\
& + \sqrt{2\epsilon(1+\epsilon)} \Big(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \Big) \Big] \\
& + T_{\perp\perp} h [\cdots]
\end{aligned}$$

Tagged DIS with deuteron: model for the IA



- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

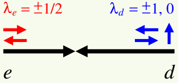
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

All SF can be written as

$F_{ij}^k = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{or}\, g_{1,2}(\tilde{x}, Q^2)\} \times \{$bilinear forms in deuteron radial **S** $[U(k)]$ and **D**-wave $[W(k)]\}$

- In the IA the following structure functions are **zero** → sensitive to FSI
  - beam spin asymmetry $[F_{LU}^{\sin\phi_h}]$
  - target vector polarized single-spin asymmetry [8 SFs]
  - target tensor polarized double-spin asymmetry [7 SFs]

Polarized structure function: longitudinal asymmetry



- On-shell extrapolation of double spin asymmetry
  - Nominator
    $d\sigma_{||} \equiv \frac{1}{4}\left[\mathrm{d}\sigma(+\tfrac{1}{2},+1) - \mathrm{d}\sigma(-\tfrac{1}{2},+1) - \mathrm{d}\sigma(+\tfrac{1}{2},-1) + \mathrm{d}\sigma(-\tfrac{1}{2},-1)\right].$
  - Two possible denominators: 3-state and 2-state

$$d\sigma^{(3)} \equiv \tfrac{1}{6}\sum_{\lambda_e}\left[\mathrm{d}\sigma(\lambda_e,+1) + \mathrm{d}\sigma(\lambda_e,-1) + \mathrm{d}\sigma(\lambda_e,0)\right],$$
$$d\sigma^{(2)} \equiv \tfrac{1}{4}\sum_{\lambda_e}\left[\mathrm{d}\sigma(\lambda_e,+1) + \mathrm{d}\sigma(\lambda_e,-1)\right];$$

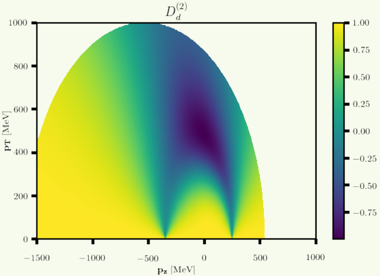
  - Asymmetries: **tensor polarization** enters in 2-state one

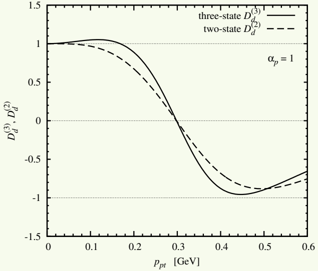
$$A_{||}^{(3)} = \frac{d\sigma_{||}}{d\sigma^{(3)}}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L}$$
$$A_{||}^{(2)} = \frac{d\sigma_{||}}{d\sigma^{(2)}}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})}$$

- Impulse approximation yields in the Bjorken limit

$$A_{||d}^{(i)} \approx D_d^{(i)}(\alpha_p, |p_{pT}|)A_{||n} = D_d^{(i)}(\alpha_p, |p_{pT}|)\frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n)F_{1n}(\tilde{x}, Q^2)}$$

Nuclear structure factors $D_d^{(3)}, D_d^{(2)}$





WC, C. Weiss, arXiv:1902.03678; in preparation

- $-1 \leq D_d^{(2)} \leq 1$ has physical interpretation as ratio of nucleon helicity density to unpolarized density in a deuteron w polarization +1
- Due to lack of OAM $D_d^{(2)} \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $D_d^{(3)}$ violates bounds due to lack of tensor pol. contribution
- $D_d^{(3)} \neq 0$ for $p_T = 0$
- $D_d^{(2)}$ closer to unity at small recoil momenta
- 2-state Asymm. also easier experimentally!!

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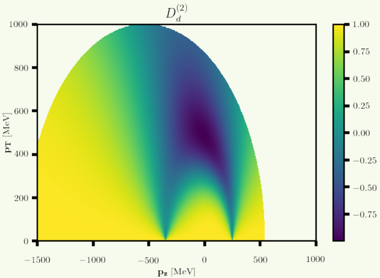

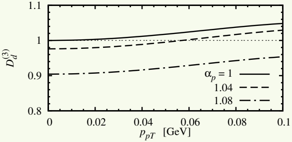

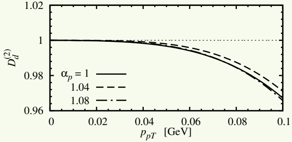

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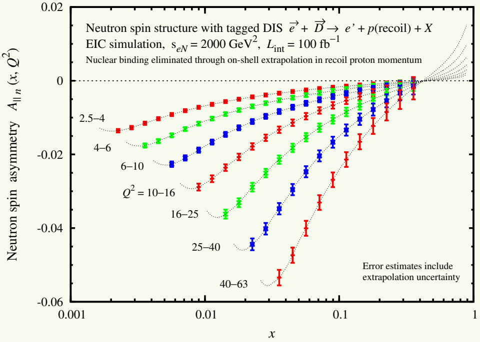


JLab LDRD arXiv:1407.3236, arXiv:1409.5768
https://www.jlab.org/theory/tag/

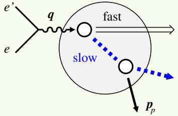
- Statistics requirements
  - Physical asymmetries $\sim 0.05 - 0.1$
  - Effective polarization $P_e P_D \sim 0.5$
  - Luminosity required $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{x s_{eN}}$, wide range of s_{eN} required!

- Precise measurement of neutron spin structure
  - separate leading- /higher-twist
  - non-singlet/singlet QCD evolution
  - pdf flavor separation $\Delta u, \Delta d$. ΔG through singlet evolution
  - non-singlet $g_{1p} - g_{1n}$ and Bjorken sum rule

Extensions

- Final-state interactions modify cross section away from the pole
  - studied for unpolarized case at EIC kinematics, pole extrapolation still feasible

    [Strikman, Weiss PRC '18]
  - dominated by slow hadrons in target fragmentation region of the struck nucleon
  - extend to $\vec{e} + \vec{d}$
  - constrain FSI models
  - non-zero azimuthal and spin observables through FSI

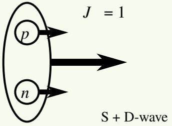


- Tensor polarized observables
- Tagging with complex nuclei $A > 2$
  - isospin dependence, universality of bound nucleon structure
  - $A - 1$ ground state recoil
- Resolved final states: SIDIS on neutron, hard exclusive channels

Conclusions

- Light ions address important parts of the EIC physics program
- Tagging and nuclear breakup measurements overcome limitations due to nuclear uncertainties in inclusive DIS → **precision machine**
- Unique observables with **polarized deuteron**: free neutron spin structure, tensor polarization
- Clear advantages in using two-state asymmetry to extract g_{1n}
- Extraction of nucleon spin structure in a wide kinematic range
- Lots of extensions to be explored!

Deuteron light-front wave function



- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]

- One obtains a Schrödinger (non-rel) like eq. for the wave function components, rotational invariance recovered
- Light-front WF obeys baryon and momentum sum rule

$$\Psi^D_\lambda(\boldsymbol{k}_f, \lambda_1, \lambda_2) = \sqrt{E_{k_f}} \sum_{\lambda_1' \lambda_2'} \mathcal{D}^{\frac{1}{2}}_{\lambda_1 \lambda_1'}[R_{fc}(k^\mu_{1_f}/m_N)] \mathcal{D}^{\frac{1}{2}}_{\lambda_2 \lambda_2'}[R_{fc}(k^\mu_{2_f}/m_N)] \Phi^D_\lambda(\boldsymbol{k}_f, \lambda_1', \lambda_2')$$

- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - $\boldsymbol{k}_f$ is the relative 3-momentum of the nucleons in the light-front boosted rest frame of the free 2-nucleon state (so not a “true” kinematical variable)