Polarized electron-deuteron deep-inelastic scattering with spectator nucleon tagging

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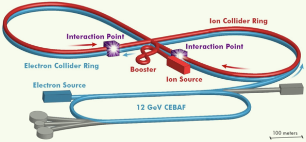
in collaboration with Ch. Weiss,
JLab LDRD project on spectator tagging
`WC, C. Weiss, arXiv:1906.11119`

GHENT UNIVERSITY

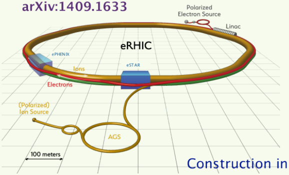
Electron-ion collider

- World's first polarised electron-proton/light ion and electron-nucleus collider. Two sites under consideration: Jefferson Lab and Brookhaven National Lab, USA. → talks by S. Fazio, P. Rossi on Fri.

JLEIC @ Jefferson Lab
arXiv:1504.07961



eRHIC @ Brookhaven National Lab
arXiv:1409.1633



Construction in 2020s

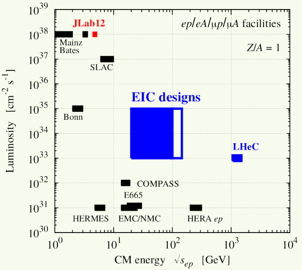
- 2012 EIC White Paper `Accardi et al., Eur. Phy. J. A 52, 9 (2016)`
- 2015 Nuclear Physics Long Range Plan: "[EIC] as the highest priority for new facility construction following completion of FRIB"
- 2017-18 National Academies of Science (NAS) Review
- Next stage: CD0 (formally establishing mission need), expected this year
- User meeting in Paris last week: `https://indico.in2p3.fr/event/18281/`

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

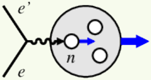
Use of light ions for high-energy scattering and QCD studies remains largely unexplored

EIC design characteristics (for light ions)

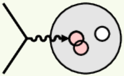


- CM energy $\sqrt{s_{eA}} = \sqrt{Z/A}\ 20 - 100\text{GeV}$ DIS at $x \sim 10^{-3} - 10^{-1}$, $Q^2 \leq 100\text{GeV}^2$
- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables
- Polarized light ions
  - ^{3}He, 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

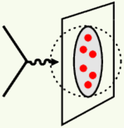
Light ions at EIC: physics objectives



- **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



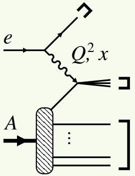
- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation

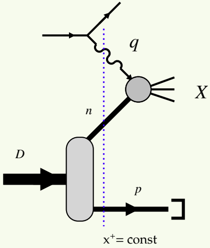


- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

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 measurements

Needed for flavor separation, singlet vs non-singlet evolution etc.

- EIC will measure **inclusive** DIS on light nuclei [d, ^{3}He, ^{3}H(?)]
  - Simple, no FSI effects
  - Compare n from ^{3}He $\leftrightarrow$ p from ^{3}H
  - Comparison n from ^{3}He, d

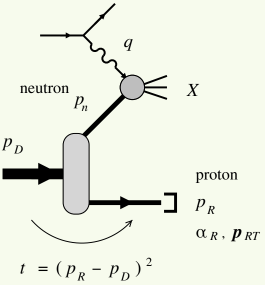
- **Uncertainties** limited by nuclear structure effects
  $\rightarrow$ binding, Fermi motion, non-nucleonic dof

- ^{3}He is in particular affected because of intrinsic Δs

If we want to aim for precision, use tools that avoid these complications

Neutron structure with tagging

- 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 ($p_p \to 0$), 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

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

- 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`)

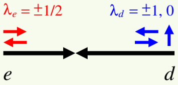
- Light-front structure of the deuteron
  - Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**

Polarized deuteron tagged DIS: cross section

- Spin 1 particle has density matrix with **8** parameters: 3 vector, 5 **tensor**
- SIDIS cross section: unpolarized + vector polarized can be copied from spin 1/2 `[Bacchetta et al., JHEP ('07)]`
  Tensor part has **23** additional structure functions, each with their unique azymuthal dependence `[WC, C. Weiss, in prep.]`
- In the impulse approximation all SF can be written as

$$F_{ij}^{k} = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{or}\, g_{1,2}(\tilde{x}, Q^2)\} \times \{\text{bilinear forms in deuteron radial wave function } f_0(k), f_2(k)\}$$

- 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]



- 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

$$d\sigma_3 \equiv \frac{1}{6}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1) + \mathrm{d}\sigma(\Lambda_e,0)\right]$$
$$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$

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

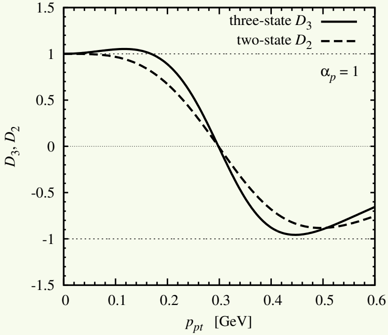
$$A_{||,3} = \frac{d\sigma_{||}}{d\sigma_3}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L}$$
$$A_{||,2} = \frac{d\sigma_{||}}{d\sigma_2}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})}$$

- Impulse approximation yields in the Bjorken limit $\left[\alpha_p = \frac{2p_p^+}{p_D^+}\right]$

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

Nuclear structure factors $\mathcal{D}_2$, $\mathcal{D}_3$

- $\mathcal{D}_2$ has physical interpretation as ratio of nucleon helicity density to unpolarized density in a deuteron with polarization $+1$. $\mathcal{D}_3$ has no such interpretation.



WC, C. Weiss, arXiv:1906.11119; in preparation

- Bounds: $-1 \leq \mathcal{D}_2 \leq 1$
- Due to lack of OAM $\mathcal{D}_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $\mathcal{D}_3$ violates bounds due to lack of tensor pol. contribution
- $\mathcal{D}_3 \neq 0$ for $p_T = 0$
- $\mathcal{D}_2$ closer to unity at small recoil momenta
- 2-state asymmetry is also easier experimentally!!

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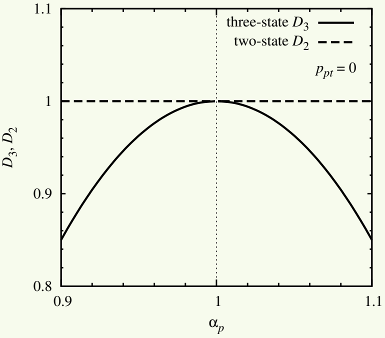

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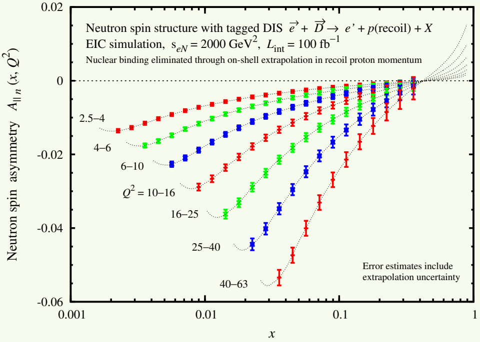
Tagging: simulations of pole extrapolation of $A_{||}$



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

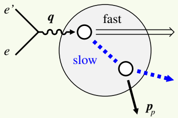
- Statistics requirements
  - Physical asymmetries $\sim 0.05 - 0.1$
  - Effective polarization $P_e P_D \sim 0.5$
  - Luminosity required $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{x s_{eN}}$, wide range of s_{eN} required!

- 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!