DIS on a polarized deuteron with spectator nucleon tagging

Wim Cosyn

Ghent University, Belgium

Spin18
Ferrara

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

Why focus on light ions at an EIC?

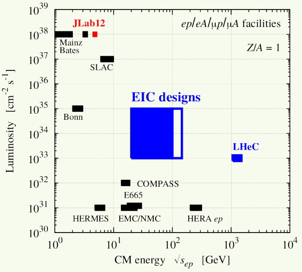
- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - coherent phenomena

- 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)

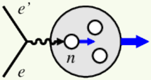


- CM energy $\sqrt{s_{eA}} = \sqrt{Z/A}\ 20 - 100\text{GeV}$ DIS at $x \sim 10^{-3} - 10^{-1}$, $Q^2 \leq 100\text{GeV}^2$
- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables

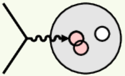
- Polarized light ions
  - ^{3}He, other @ eRHIC
  - d, ^{3}He, other @ JLEIC (figure 8)
  - spin structure, polarized EMC, tensor pol, ...

- Forward detection of target beam remnants
  - diffractive and exclusive processes
  - coherent nuclear scattering
  - nuclear breakup and tagging
  - forward detectors integrated in designs

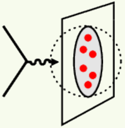
Light ions at EIC: physics objectives



- **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



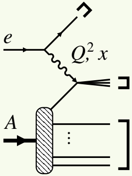
- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation

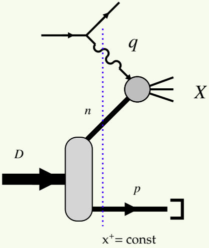


- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

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

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

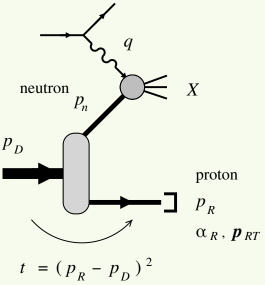
- **Uncertainties** limited by nuclear structure effects (binding, Fermi motion, non-nucleonic dof)

- ^{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

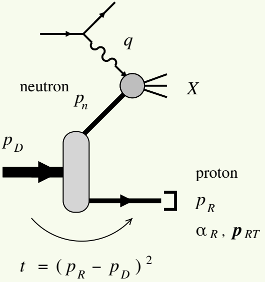
- Proton tagging offers a way of controlling the nuclear configuration



- 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

- Suited for colliders: no target material ($p_p \to 0$), forward detection, polarization.
  fixed target CLAS BONuS limited to recoil momenta ~ 70 MeV

Pole extrapolation for on-shell nucleon structure



- Allows to extract free neutron structure
  - Recoil momentum p_R controls off-shellness of neutron $t' \equiv t - m_N^2$
  - Free neutron at pole $t - m_N^2 \to 0$: "on-shell extrapolation"
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects `[Sargsian,Strikman PLB '05]`

- D-wave suppressed at on-shell point → neutron $\sim 100\%$ polarized

- Precise measurements of neutron (spin) structure at an EIC

Theoretical Formalism

- Tagged spectator DIS is SIDIS in the target fragmentation region

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

- 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

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

- 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

- We consider polarization wrt photon momentum
- On-shell extrapolation of double spin asymm.

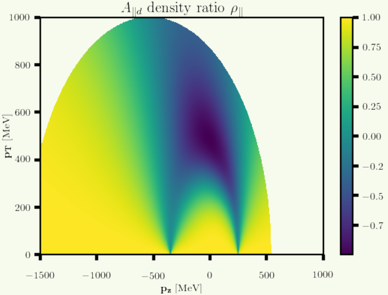
$$A_{||} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + \sigma(--)}{\sigma(++) + \sigma(-+) + \sigma(+-) + \sigma(--)}[\phi_h \, \text{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_L LT} + \epsilon F_{T_{LL} L})}$$

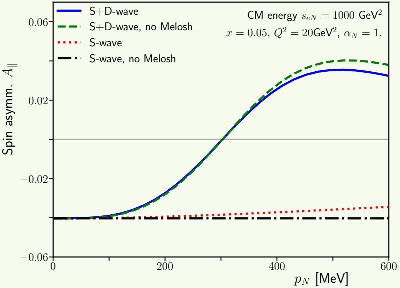
- SF are tagged, depend on recoil momentum:
$F_{LS_L} = 2[g_{1d}(x, Q^2, p_p) - \gamma^2 g_{2d}(x, Q^2, p_p)] \qquad [\gamma = 2Mx/Q]$
- Denominator is **not** the unpolarized cross section, you have a contribution from **tensor** polarization
- Impulse approximation yields

$$A_{||} = \rho_{||} \frac{D_1 g_{1n}(\tilde{x}, Q^2) + D_2 g_{2n}(\tilde{x}, Q^2)}{2(1 + \epsilon R_n) F_{1n}(\tilde{x}, Q^2)} \approx \frac{D_1 \rho_{||}}{2(1 + \epsilon R_n)} \frac{g_{1n}(\tilde{x}, Q^2)}{F_{1n}(\tilde{x}, Q^2)}$$

  - $\rho_{||}$: ratio of polarized deuteron densities
  - $D_2 \propto \gamma^2$ power suppressed

Polarized structure function: longitudinal asymmetry

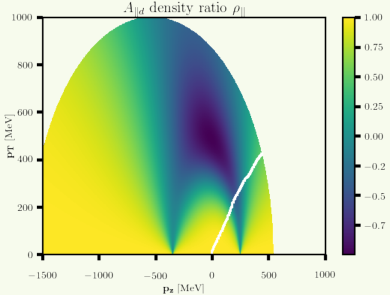


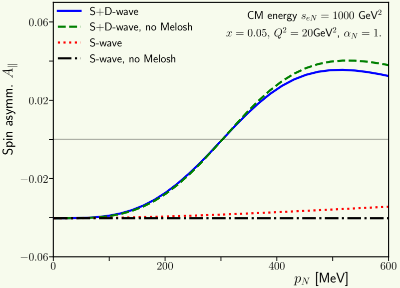


- $\rho_{||} \equiv 1$ for $p_T = 0$
- rotational invariance of the deuteron system recovered in the non-rel limit

- Clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

Polarized structure function: longitudinal asymmetry





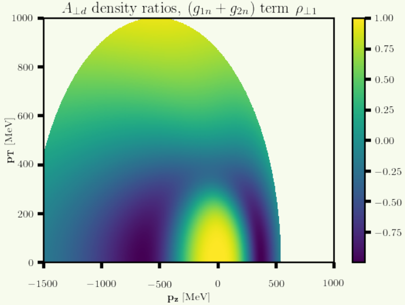
- $\rho_{||} \equiv 1$ for $p_T = 0$
- rotational invariance of the deuteron system recovered in the non-rel limit

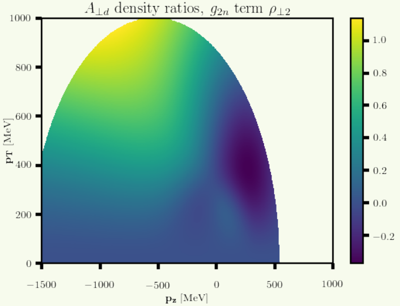
- Clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

Polarized structure function: transverse asymmetry

- Similar expressions hold for

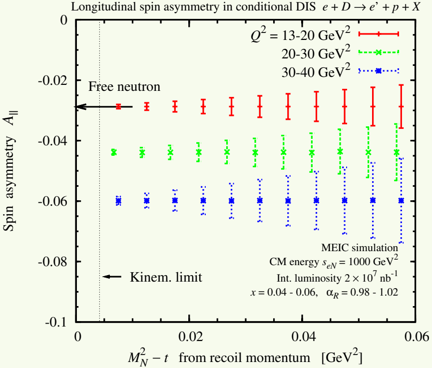
$$A_\perp[\phi_h \text{ avg}] = \tilde{\gamma}_N \frac{d_1 \rho_{\perp 1}(g_{1n} + g_{2n}) + d_2 \rho_{\perp 2} g_{2n}}{2(1+\epsilon R_n) F_{1n}} + \text{power suppr. terms}$$





- $\rho_{\perp 2} \propto \boldsymbol{p}_T$
- rotational invariance again recovered in the NR limit

Tagging: simulations of $A_{||}$

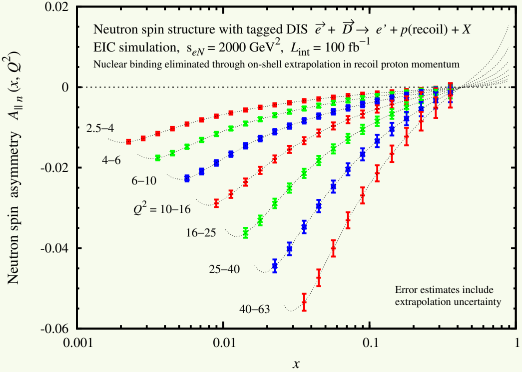


`JLab LDRD arXiv:1407.3236, arXiv:1409.5768`
`https://www.jlab.org/theory/tag/`

- D-wave suppr. at on-shell point $\to$ neutron $\sim$ 100% polarized
- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)
- Statistics requirements
  - Physical asymmetries $\sim 0.05 - 0.1$
  - Effective polarization $P_e P_D \sim 0.5$
  - Luminosity required $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Tagging: simulations of $A_{||}$

On-shell extrapolation of double spin asymm. $A_{||} = D\frac{g_{1n}}{F_{1n}} + \cdots$



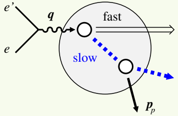
- As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{x s_{eN}}$, wide range of s_{eN} required!

- 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
- Extraction of nucleon spin structure in a wide kinematic range
- Lots of extensions to be explored!