EIC Science with Polarized Light Ions

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EICUG 18

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GHENT UNIVERSITY

Topical workshop

- Held at Ghent University, February 5-9 2018
  Organizers: W. Cosyn (Ghent), A. Deshpande (SBU/BNL), J. Ryckebusch (Ghent), Ch. Weiss (JLab)
- ~40 participants from both high-energy scattering / QCD and low-energy nuclear structure community
- Talks online @ https://www.jlab.org/indico/event/246/

Why focus on light ions?

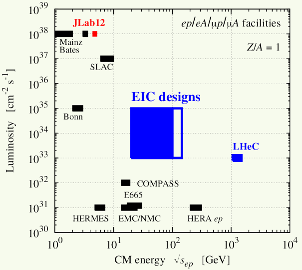
- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - coherent phenomena

- 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

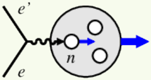
Use of light ions for high-energy scattering and QCD studies remains largely unexplored

EIC design characteristics (for light ions)

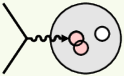


- CM energy $\sqrt{s_{eA}} = \sqrt{Z/A}\, 20 - 100\text{GeV}$
  DIS at $x \sim 10^{-3} - 10^{-1}$, $Q^2 \leq 100\text{GeV}^2$
- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables
- Polarized light ions
  - ^{3}He,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

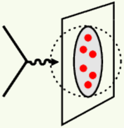
Light ions at EIC: physics objectives



- **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



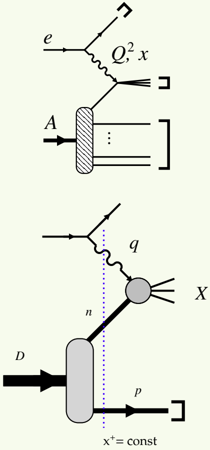
- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation



- **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

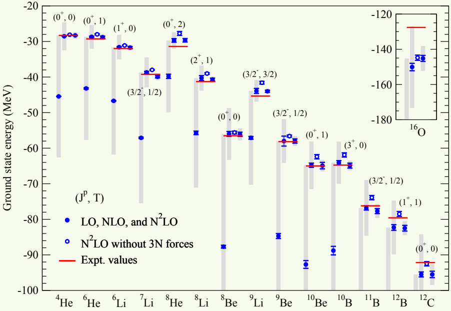
Theory: high-energy scattering with nuclei



- 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

Theory: nuclear structure calculations

- First principle NR calculations available for light ions



LENPIC collab, arXiv:1807.02848

- Controlled expansion and hierarchy using χEFT for two- and three- body forces
- Variety of methods: finite-basis, no-core SM, GFMC, lattice EFT
- Fadeev methods for ^{3}He reactions

These tools need to be extended for applications in high-energy scattering

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

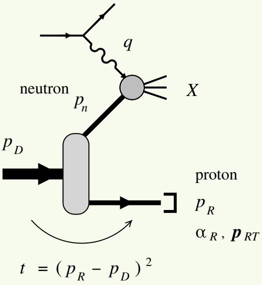
- **Uncertainties** limited by nuclear structure effects (binding, Fermi motion, non-nucleonic dof)

- ^{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

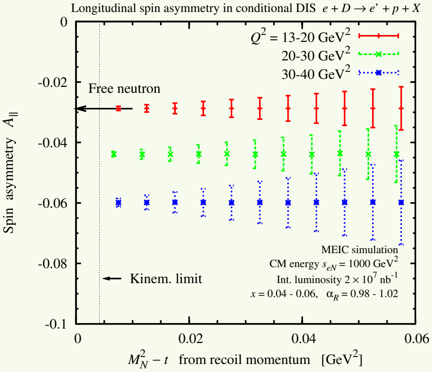
- Suited for colliders: no target material ($p_p \to 0$), forward detection, polarization.
  fixed target CLAS BONuS limited to recoil momenta ~ 70 MeV
- Measurements of neutron structure at an EIC over a wide kinematic range at percent-level accuracy

Tagging: polarized neutron structure

- Same tagging techniques can be applied in polarized deuteron DIS

On-shell extrapolation of double spin asymm.

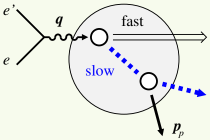
$$A_{||} = \frac{\sigma(++)-\sigma(-+)-\sigma(+-)+\sigma(--)}{\sigma(++)+\sigma(-+)+\sigma(+-)+\sigma(--)}[\phi_h \text{avg}] = \frac{F_{LS_L}}{F_T+\epsilon F_L} = D\frac{g_{1n}}{F_{1n}} + \cdots$$

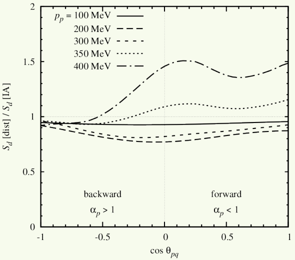


JLab LDRD arXiv:1407.3236, arXiv:1409.5768
https://www.jlab.org/theory/tag/

- D-wave suppr. at on-shell point → neutron ∼ 100% polarized
- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)
- Statistics requirements
  - Physical asymmetries ∼ 0.05 − 0.1
  - Effective polarization $P_e P_D \sim 0.5$
  - Luminosity required $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- Precise measurement of neutron spin structure
  - non-singlet/singlet QCD evolution
  - pdf flavor separation $\Delta u, \Delta d$. ΔG through singlet evolution

 Final-state interactions in tagging





Strikman, Weiss, PRC7 035209 ('18)

- **Issue** in tagging: DIS products can interact with spectator → rescattering, absorption
- Dominant contribution at intermediate $x \sim 0.1 - 0.5$ from "**slow**" hadrons that hadronize inside nucleus
- Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.
- FSI vanish at the pole → pole extrapolation **still feasible**

→ Talk Ch. Weiss this afternoon

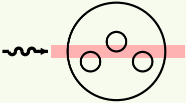
Nucleon interactions

How do nucleon interactions emerge from QCD?

- **Short-range structure** of nuclei, NN force at very short distances
  - Quasi-elastic d breakup
  - Short-range correlation studies: (multi-)nucleon knockout w high ($>k_F$) initial momenta, 3N correlations?
- **Medium modification** of nucleon properties embedded in nucleus: EMC effect, other quantities
  - Q^2, isospin ($N \neq Z$) dependence
  - gluon EMC effect
  - spin-dependent EMC effect on polarized light ions
  - tagging: what intra-nucleon distances play a role?

JLab12 will measure some of these processes, but open questions will remain that can be addressed at EIC

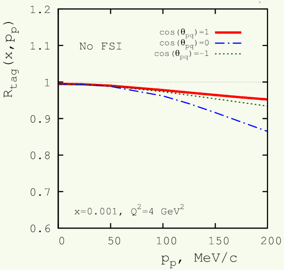
Nuclear interactions: Coherence

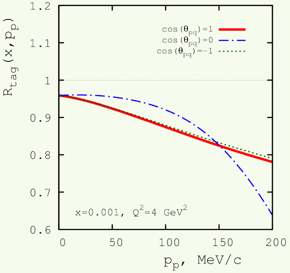


- interaction of high-energy probe with coherent quark-gluon fields

- **Shadowing** is manifestation of coherence
  - **Diffractive** DIS at $x \ll 0.1$: 10–15% of events at HERA
  - **Interference** between diffractive amplitudes → reduction of cross section, leading twist
  - Extensively studied in heavy nuclei
  - Is especially clean in the **deuteron**, effects can be calculated
  - **Dynamics** of shadowing can be explored in tagging: **single** and **double**
  - Tagging also results in **FSI** between the slow n and p

Shadowing: tagged DIS





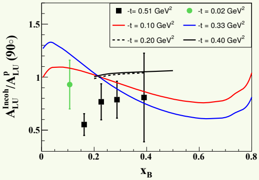
[Guzey,Strikman,Weiss; in preparation]

- Explore shadowing through recoil momentum dependence
- Shadowing **enhanced** in tagged DIS compared to inclusive
  - enhancement factor from AGK rules
  - shadowing term drops slower with p_R than IA
- Large FSI effects in diffractive amplitudes ($\sim 40\%$), also at zero spectator momenta due to orthogonality of *np* state to deuteron
- Effects smaller in tagged as diffractive are $\sim 10\%$ of total events

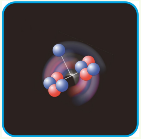
Nuclear imaging

Images of nuclei in terms of quark and gluon dof

- Deeply virtual Compton scattering → **GPDs**
  - coherent: transverse imaging of nuclei
  - incoherent: medium modification of transverse nucleon densities
- **Tagged** DVCS provides additional control over initial configuration
- Transverse **gluon** structure of light ions (d, ^{4}He, ^{3}He) with exclusive coherent J/ψ production
- Clustering & spin-orbit phenomena in nuclear structure of light nuclei



^{4}He DVCS
M. Hattawy et al. [CLAS]



^{9}Be Clustering

Nuclear imaging: tensor polarization

- Tensor polarization in d probes **nuclear effects**
- little explored in high-energy scattering
- inclusive b_1 result from HERMES: no conventional nuclear calculation reproduces data
- unique features: eg access **gluon transversity**
- Tagged cross section yields 23 additional structure functions with specific azimuthal dependences [Cosyn,Sargsian,Weiss, in prep.]

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

- T-odd SF [DSA] are zero in impulse approximation → sensitive to FSI

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
- Light-front nuclear structure input needed for initial state in theoretical frameworks → community enthusiastic
- Beginning of a process: future meetings planned, R & D in progress
- Summary document in preparation!

Polarized light-ion physics with EIC

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Potential for great progress!
We hope that light ions can be discussed on the same level as the proton and heavy ion program