### Thoughts on EIC early running with eA

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# **Electron-Ion Collider**

- First collider of its kind
  - Nuclei from D to Au, Pb and in between
  - Polarized electrons, light nuclei

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

...give a talk on impactful measurements that we would be able to make given these constraints





- Nuclear breakup
- Coherent scattering
- Diffraction

- Control over initial nuclear configurations
- Many novel measurements possible
- Needs more theory input
  - Final-state interactions

# EIC physics with nuclei







- Partonic structure of nuclei
  - Collinear pdfs, diffractive
  - 3D imaging of nuclear bound states (TMDs, GPDs)
  - Neutron structure (polarized)
- Nuclear interactions and structure
  - Medium modifications
  - Short-range correlations, QCD origin of core of NN interaction
  - Shape deformations
  - Non-nucleonic components
- Coherence and saturation
  - $\circ$  Interaction of high-energy probe with coherent quark-gluon fields  $\rightarrow$  talk Salazar
- Hadronization in the medium
  - Space-time picture
  - Transport of hadrons in cold hadronic matter

## Nuclear pdfs

- First collider with ep, ed, eA
  - Global analysis (biases)
  - Day 1 measurements (high precision, new x & Q<sup>2</sup> regions)
  - Fits without assumed A-dependence

- Medium modifications
  - (anti)shadowing, EMC
  - First for gluons
  - $\circ$  Q<sup>2</sup>, A dependence





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## Nuclear gluons

- Open charm production
  - $\rightarrow$  photon-gluon fusion
  - $\rightarrow$  10%-1% of DIS events
  - $\rightarrow$  O(10E6-10E5) events for 10fb<sup>-1</sup>

Probes the gluon density at fixed scale
 → heavy quark mass

• Gluonic EMC-effect / anti-shadowing

[E. Chudakov et al., JoP: Conf Series 770 012042 ('16)]
[E. C. Aschenauer et al., PRD 96 114005 ('17)]
[M. Kelsey et al., PRD 104 054002 ('21)]



## Nuclear diffractive pdfs

- Diffraction
  - large rapidity gap between target/current fragmentation regions
  - Colorless exchange in *t*-channel (Pomeron, Reggeon, etc.)
- Observed at HERA  $\rightarrow$  ~15% at low x
  - More (25%) expected at EIC (saturation)
- Never measured for eA
- Coherent/incoherent diffraction

   → nuclear radius, global structure
   → nucleon/subnucleon fluctuations
   → can ePIC discriminate?
- Sensitive probe to gluon saturation
  - g<sup>2</sup>(x,Q<sup>2</sup>)









# Neutron structure with light ions (d, <sup>3</sup>He)

- Needed in flavor separation of parton correlation functions
- Measure in inclusive DIS (of course)
  - ↔ uncertainties in inclusive limited due to nuclear binding effects
  - $\hookrightarrow$  <sup>3</sup>He affected by intrinsic  $\Delta$ s
- Workaround: measure spectator nucleon(s)/fragments in breakup
  - $\hookrightarrow \text{control initial configuration}$
  - $\hookrightarrow$  identify active nucleon
- Free Neutron structure (on-shell extrapolation at small momenta) [Sargsian, Strikman PLB 639 ('06)]

→ validate with neutron tagging for ``tagged" proton structure

- Medium modifications (larger spectator momenta)
  - ↔ select nuclear configurations responsible for modifications [EMC/(anti)shadowing]
  - $\hookrightarrow$  needs disentangling from spectator FSI effects
  - $\hookrightarrow$  rates drop due to deuteron momentum distribution
- Related: meson( $\pi/K$ ) DIS/FF studies in ep (and ed) with Sullivan process



### Neutron structure extraction: on-shell extrapolation

 $F_{2d} = [2(2\pi)^3] S_d(\alpha_p, p_{pT})[\text{unpol}] F_{2n}(\tilde{x}, Q^2)$ 



[Jentsch, Tu, Weiss, PRC21]



 $\rightarrow$  Final state (interactions) more complicated

## Neutron structure: tagging on steroids

- Same procedure but more complicated hard process or tagging than tagged DIS → rates sufficient?
- Tagged SIDIS for neutron TMDs  $\Rightarrow e + d \rightarrow \pi + (X) + p$  $\Rightarrow e + {}^{3}He(pol) \rightarrow transverse n SSA?$
- Tagged diffractive
  - $\hookrightarrow$  differential study of nuclear shadowing
- Tagged exclusive
  - $\hookrightarrow$  incoherent DVMP?
  - $\hookrightarrow$  coherent (unpolarized?)
- Tag non-nucleonic components of nuclear wave function
  - $\hookrightarrow \Delta \text{ tagging for ed}$
  - ↔ short-range nature of NN-force (link with QCD dof)

Smaller cross section

## Diffractive deuteron break up: gluon density modification



- Double spectator tagging
- Study gluon densities as a function of nucleon momenta
- YR: ed 18x110 10fb<sup>-1</sup> [Z. Tu et al. PLB'20]



Z. Tu et al, PLB'21

#### **Target Fragmentation**



- Underexplored!
- Fracture functions (x<sub>F</sub>)
- Hadronization of target after parton removal
- EIC?
- $\hookrightarrow$  x-dependence
- $\hookrightarrow$  spin-dependence
- $\hookrightarrow$  quark vs gluon removal
- $\hookrightarrow$  correlations with current region
- Feeds into FSI for nuclear breakup reactions ("slow" hadrons from TF)

[R. Esha @ POETIC '25]

## Hadronization and particle propagation in medium

• If hadronization is in- or outside nucleus depends on *A*, energy and hadron mass

 $\hookrightarrow$  space-time picture poorly understood

- $\hookrightarrow$  heavy quarks hadronize within  $\rightarrow$  differentiate between energy loss / absorption
- Hadron multiplicities, jet measurements
- q<sup>ˆ</sup> (=<t<sub>medium</sub>>/L) quantifies parton energy loss
   → not well constrained at the moment
  - → affects SSA in nuclear SIDIS



## Hadronization and particle propagation in medium

• SIDIS: extraction of nFF



Inclusive and heavy flavor jet observables
 ⇒ medium effects in npdf and jet-medium interaction

- Ratios to inclusive or w different jet radii eliminates npdf effects
- Neutrons in ZDC give handle on centrality of collision [Beagle, W. Chang et al, 2204.11998]



[Li, Liu, Vitev, PLB '21, 2303.14201]

### Conclusions

- EIC physics program aims to provide answers to key questions in QCD
- Far-forward detectors are essential in tagging / breakup measurements in eA
- Lots of firsts!!!
  - Who knows what surprises these bring...
- Lots of work to be done from the theory side as well
  - Baseline calculations needed to quantify deviations (medium modification)
  - Final-state interactions (nuclear, partonic)
  - Precision calculations possible with realistic nuclear input for light ions
- Many things I didn't cover here...



#### Summer School "Light-ion physics in the EIC era: From nuclear structure to high-energy processes"



#### 19–27 Jun 2025 Florida International University, Miami, FL US/Eastern timezone

#### Lecturers include:

Wim Cosyn (Florida International University) Alex Gnech (Old Dominium University) Vadim Guzey (Jyvaskyla University) Dien Nguyen (University of Tennessee Knoxville) Saori Pastore (Washington Unicersity St. Louis) Jackson Pybus (Los Alamos National Lab) Matteo Rinaldi (Perugia University & INFN) Misak Sargsian (Florida International University) Zhoudunming Tu (Brookhaven National Lab) Christian Weiss (Jefferson Lab) Others TBC

#### Organizers:

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