Towards a 3D Landscape of Nucleons and Nuclei

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- Introduction
- Partonic imaging of the nucleon in position and momentum
- Partonic description of nuclei in position and momentum
- Summary
Unified View of Nucleon Structure

\( W_p^u(x, k_T r_T) \) Wigner distributions

Transverse Momentum Dist.

Generalized Parton Dist.

\[ \text{TMDs} \quad d r_T \quad d^2 k_T \]

\[ \text{TMD} \quad f_1^u(x, k_T), \quad h_1^u(x, k_T) \]

\[ \text{GPDs} \quad \delta z_1 \sim 1/Q \]

Tomography

Parton Distribution Functions

\[ Q^2 = 10 \text{ GeV}^2 \]

PDFs

\[ f_1^u(x), \ldots \quad h_1^u(x) \]

\[ 1D \]

Form Factors

\[ G_E(Q^2), \quad G_M(Q^2) \]

dx & Fourier Transformation

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Science Goals

- Exploring our understanding of QCD
  - Factorization
  - Evolution, universality
- Distributions of confined partons
  - Charge and matter distributions, pressure distribution and spin distribution.
- Dynamics of confined motion of partons
  - Orbital motion, spin-orbit correlations, phases
- Hadron formation, hadron propagation, coherence.
- Rest frame vs infinite momentum frame
- Models of the nucleon
- Lattice QCD
  - Moments of pdfs, quasi-pdf...

Question in Nuclear Physics:

When does a nucleus behaves as one coherent collection of partons?
New theoretical framework within QCD
- Non-local matrix elements linked to measurements
- Wigner distribution for a unified picture
- GPDs, TMDs: 3D images in space and momentum

Valence Quarks: Proof of principle achieved using JLab 6 GeV data, 12 GeV data are forthcoming in the short term.

Gluons and Sea quarks: EIC is the key facility

3D imaging is intimately linked to profound questions about intrinsic properties of the system in relation to its partonic constituents
- Confinement size of charge and of matter, total mass, total spin

The nucleus: a laboratory to study partons coherence, partons propagation, partons saturation, parton hadronization.
Science in 3-Dimensions

3D simulation of 15M$_{\odot}$ supernova (ORNL)

Predicted quark TMD for a polarized proton (accessible with JLab @ 12 GeV)

Prediction informed by A global analysis of data from HERMES, COMPASS and Jlab 6

X=0.1

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Mimivirus imaged at LCLS (SLAC)
Experimental tools to access GPDs & TMDs

- **Semi-Inclusive reactions**: \( e+p/A \rightarrow e'+h(\pi,K,...)+X \)
  - *Detect scattered lepton in coincidence with identified hadrons (mesons)*
  - Semi-Inclusive Deep Inelastic Scattering (SIDIS)
  - **Challenge**:
    - High polarized luminosity combined with large acceptance detectors
    - 5 key variables \( x, Q^2, z, p_T \) and angle between leptonic and hadronic plane
    - Fine binning needed

- **Exclusive reactions**: \( e+p/A \rightarrow e'+p'/A'+ (\gamma, \pi, K,...) \)
  - *Detect all final states including recoiling nucleon or nucleus*
  - Deep Virtual Compton Scattering (DVCS) when detecting the real photon \( \gamma \)
  - Deep Virtual Meson Production (DVMP) when detecting \( \pi, \phi, \omega, J/\Psi, \Upsilon \)
  - **Challenge**:
    - High polarized luminosity combined with large acceptance detectors
    - 4 key variables \( x, Q^2, t \) and angle between leptonic and production plane \( \phi \)
    - Fine binning needed
Deeply Virtual Compton Scattering

A clean probe of GPDs

- At large $Q^2$: QCD factorization theorem
- At twist-2: 4 quark helicity conserving GPDs:
  \[ H_q(x, \xi, t, Q^2), E_q(x, \xi, t, Q^2), \ldots \]
- Key: $Q^2$ leverage needed to test QCD scaling
- High statistics required for a clean extraction

\[ \sigma(ep \rightarrow ep\gamma) \propto \frac{d\sigma}{dx_B dQ^2 dt d\phi} \]
\[ Q^2 = -q^2 = -(k - k')^2 \]
\[ t = (p' - p)^2 \]
\[ x_B = Q^2 / 2p \cdot q \]
\[ t \ll Q^2, \xi \rightarrow \frac{x_B}{2 - x_B} \]
Separating GPDs Through Polarization Measurements of Compton FF

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma} \]

\[ \xi = x_B/(2-x_B) \]

\[ k = -t/4M^2 \]

**Polarized beam, unpolarized target:**

\[ \Delta\sigma_{LU} \sim \sin\phi\{F_1H + \xi(F_1+F_2)\tilde{H} + kF_2E\}d\phi \]

Kinematically suppressed

**Unpolarized beam, longitudinal target:**

\[ \Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + ... )\}d\phi \]

**Unpolarized beam, transverse target:**

\[ \Delta\sigma_{UT} \sim \sin\phi\{k(F_2H - F_1E) + .... \}d\phi \]

Global analysis of polarized and unpolarized data needed for GPDs separation
Proton Beam Spin Asymmetry $A_{LU}$ (CLAS 12 projections)

80 days @ $10^{35}$ cm$^{-2}$s$^{-1}$
Polarized beam at 85%

$A = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$

$\langle Q^2 \rangle$ for $H(x,\zeta=x,t)$

E12-06-009
Projected Proton Transverse Profile for quarks and gluons

JLab with CLAS12
Valence quarks

Model profile
Projected error band

$Q^2 = 3.75 \text{ GeV}^2$

$\frac{q(b_{\perp} x_B)}{(fm^{-3})} = FT[H_{N\chi}(x_{\perp} b_{\perp})]$
The Approved SIDIS Experiments in the 12 GeV Era at JLab

- **Hall A** (polarized $^3$He and NH$_3$)
  - **Super Bigbite Spectrometer**
    - $E12-09-018$: SIDIS, 64d A-
  - **SoLiD**
    - $E12-11-018$: Target Single Spin Asymmetries in SIDIS ($e,e\pi^\pm$) Reaction on a Transversely Polarized Proton Target.
    - $E12-10-006$: Target Single Spin Asymmetries in SIDIS ($e,e\pi^\pm$) Reaction on a Transversely Polarized $^3$He target at 8.8 and 11 GeV.
    - $E12-11-007$: Asymmetries in SIDIS ($e,e\pi^\pm$) Reaction on a Lontitudinally Polarized $^3$He target at 8.8 and 11 GeV.

- **Hall B** (unpolarized and polarized NH$_3$, ND$_3$, HD)
  - **CLAS12**
    - $C12-11-111$: SIDIS on Transversely Polarized Target (HDICE)
    - $C12-12-009$: Measurement of transversity with di-hadrons production in SIDIS with transversely polarized target (HDICE)
  - **E12-06-112**: Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV, 38d A-
  - **E12-09-008**: Studies of the Boer-Mulders Asymmetry in Kaon Electroproduction with Hydrogen and Deuterium Targets, 38d A-
  - **E12-07-107**: Studies of Spin-Orbit Correlations with Longitudinally Polarized Target, 38d A-
  - **E12-09-009**: Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with polarized hydrogen and deuterium targets, 38d B+
  - **E12-06-112A/E12-09-008A**: Semi-Inclusive Lambda electroproduction in the Target Fragmentation Region.
  - **E12-06-112B/E12-09-008B**: Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium.

- **Hall C** (unpolarized targets)
  - **SMS-SHMS**
    - $E12-06-104$: Measurement of the ratio $R = L/\sigma T$ in SIDIS, 30d A-
    - $E12-13-007$: Measurement of Semi-Inclusive $\pi^0$ Production as Validation of Factorization, 40d A-

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Nuclear Physics with Partons; A New Paradigm

- Direct 3D partonic tomography using Coherent DVCS and DVMP on nuclei
- Investigate nuclei beyond the sum of nucleons
- Studying coherent phenomena at the partonic level
- Involving lattice to explore new phenomena at the partonic level
- Providing lattice data in the phase space that is not available
What do we know about $^4\text{He}$?

A. Camsonne et al. PRL 112, 132503 (2014)

$^4\text{He}$ Charge form factor

Nucleonic description

J. Seely et al., PRL 103, 202301 (2009)

EMC effect
A first DVCS experiment was performed at Jefferson Lab using a 6 GeV beam. It is JLab E08-024 performed with CLAS in Hall B.

\(^4\text{He}\) is a nucleus that can be described by one chiral-odd GPD \(H_A(x, \xi, t)\).

Two channels are accessible with nuclear targets a coherent and incoherent channel; we consider the more potent being Coherent DVCS.

The challenge: luminosity, exclusivity and small phase space at 6 GeV beam energy.

M. Hattawy et al. PRL 119 (2017) no.20, 202004
A follow-up JLab Proposal For CLAS 12
Partonic structure of nuclei, W. Armstrong et al.,

Spokespeople: W. Armstrong, N. Baltzell, R. Dupré, K. Hafidi, M. Hattawy, Z.-E. M (contact), M. Paolone

CLAS12 Detector

- CLAS12 Solenoid
- Si-tracker
- Forward TOF Counters
- High Threshold Cherenkov Counter (HTCC)
- CLAS12 Torus
- Electromagnetic calorimeters
- Low Threshold Cherenkov Counters (LTCC)
- Drift Chambers

ALERT detector

- IPN Orsay
- Argonne
- Outer wall
- Clear space surrounded by a Kapton wall
- Target
- Drift chamber
- Scintillators array covered by a light proof layer

→ 300 mm long
→ 90 mm diameter

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It is proposed to measure the partonic structure of $^4$He, namely quarks and gluons GPDs using DVCS and DVMP (phi production).

For exclusivity CLAS12 detector will be used in combination with a new recoil detector known as ALERT.

Advantages:
- Wider kinematic range
- Higher statistics allowing 3D binning
- More precise CFF extractions
Projected data with CLAS12 and ALERT: Valence Quarks

Asymmetry

\[ A_{LU} \]

\[ \phi_h \text{ [deg.]} \]

\[ 0.17 < x_B < 0.23 \]

\[ 0.12 < -t < 0.17 \]

\[ \chi^2 / \text{ndf} \quad 5.419 / 10 \]

\[ \text{Re}(H_A) \quad 7.39 \pm 1.96 \]

\[ \text{Im}(H_A) \quad 7.176 \pm 1.478 \]

Imaginary Part of GPD \( H_A \)

\[ \text{Im}(H_A) \]

\[ -t \text{ [GeV}^2\] ]

- 0.05 < \( x_B < 0.17 \)
- 0.17 < \( x_B < 0.23 \)
- 0.23 < \( x_B < 0.50 \)

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Projected data with CLAS12 and ALERT: Gluons

Deep Electroproduction of phi with subsequent phi decay into K⁺K⁻
Charge and matter density profiles in $^4$He: Projected Results

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Coherent production at an EIC using $J/\psi, \phi$ Production

**EIC White paper**

**$J/\psi$**

- $\frac{d\sigma}{dt} = 10 \text{fb}^{-1}/A$
- $1 < Q^2 < 10 \text{ GeV}^2$
- $x < 0.01$
- $\ln(\tau_{\text{decay}}) < 4$
- $p(\tau_{\text{decay}}) > 1 \text{ GeV/c}$
- $\delta t/t = 5\%$

**$\phi$**

- $\frac{d\sigma}{dt} = 10 \text{fb}^{-1}/A$
- $1 < Q^2 < 10 \text{ GeV}^2$
- $x < 0.01$
- $\ln(\tau_{\text{decay}}) < 4$
- $p(\tau_{\text{decay}}) > 1 \text{ GeV/c}$
- $\delta t/t = 5\%$
Challenges with Nuclei

- Jefferson Lab will provide information in the valence region
  - Coherent DVCS is safer, in terms of factorization, than coherent DVMP for the energy range involved.
  - The decrease in cross section due to the form factor requires CLAS12 high luminosity $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and higher.
  - Exclusivity requirement difficult for fixed heavy targets
  - The $Q^2$ should be large enough to insure factorization and the handbag diagram approach.

- EIC will provide information on the sea and gluon dominated region
  - Coherent DVCS and DVMP in a wide kinematic range will be accessible
  - DVMP with heavy quarkonia can provide more direct information on gluons
  - Recoiling nuclei will a little be easier to detect than in fixed target experiments
  - The luminosity is critical for the DVCS process for zero spin.
One of the transverse momentum dependent distribution functions is known as the Boer-Mulders function. It corresponds to transversely polarized quarks in unpolarized nucleons. The observable that contains the Boer-Mulders function is the angular modulation of the hadron plane with respect to the lepton plane. It would be important to understand the EMC effect in the transverse momentum dependent distributions in comparison to the longitudinal case. With the Boer-Mulders function there is no need to polarize the target and separate structure effect from spin effects.

JLab 12 will start such a program using nuclear targets.

EIC will be the ultimate machine for such studies since it has wide kinematic flexibility to validate the global analysis of data.

The challenge is having high luminosity and thus statistics to be able to provide bin in 5 –dimensions $x, Q^2, z, P_T, \phi - \phi_s$. 
The 3D landscape of nucleon and nuclei is challenging but not impossible.

JLab 12 GeV is poised to make progress toward 3D imaging of the valence quark region of light nuclei.

An EIC with high polarized luminosity and variable energy with comprehensive recoil detection is key to probe the gluonic and sea quark landscape of nuclei.

Lattice calculations need to use the data for benchmark but should also guide the experiments in the corners of the phase space not accessible by experiment.
THANK YOU