Nuclear generalized parton distributions at an EIC

Vadim Guzey

Jefferson Laboratory

“Physics at a High Energy Electron-Ion Collider”
INT, Seattle, October 22, 2009
Outline

• Introduction: why to study nuclear generalized parton distributions

• Leading twist theory of nuclear shadowing
  M. Strikman's talk

• Leading twist nuclear shadowing and nuclear generalized parton distributions

• Summary
Introduction: Generalized parton distributions

• The partonic structure of hadrons (nucleon and nuclei) is studied in high energy scattering with a large momentum transfer that enables one to resolve the short-distance parton structure of the target.

• Collinear factorization theorems enable one to introduce universal (process-independent) distributions of partons in the target and to study their $Q^2$ dependence (DGLAP).

• There are several kinds of PDFs: usual PDFs, diffractive PDFs, and generalized parton distributions

• In my talk, I will discuss nuclear generalized parton distributions (GPDs) at large energies that can be accessed in hard exclusive processes with nuclei (nuclear DVCS) at an EIC.
Introduction: GPDs (Cont.)

Deeply virtual Compton scattering (DVCS)

Form factors

Timelike Compton scattering

Exclusive meson production, deep virtual/ large t

GPDs

3D picture of hadrons, parton angular momentum

Parton distributions, DIS

Wide angle Compton scattering, $p\bar{p} \rightarrow \gamma\gamma$
Generalized parton distributions in nuclei

Complimentary to proton GPDs

- nuclear GPDs involve proton and neutron GPDs, i.e. indirect info on nucleon GPDs
- DVCS on quasi-free nucleon in nuclei (incoherent DVCS) probes the nucleon GPDs
- The only way to measure neutron GPDs, JLab, DVCS on deuteron, 2007

Traditional nuclear effects enhanced

- off-diagonal EMC effect
- nuclear shadowing (this talk)

“New” nuclear effects

- medium modifications of bound nucleon GPDs
- non-nucleon degrees of freedom
Nuclear shadowing in DIS with nuclei

Inclusive DIS with nuclear targets measures nuclear structure function $F_{2A}(x,Q^2)$

Ratio of nuclear to deuteron structure functions

- Global fits to extract nuclear PDFs lead to large uncertainties at small $x$
  S.Kumano's talk

- Alternative to fitting: dynamical models of nuclear shadowing:
  -- LT theory of nuclear shadowing
  M. Strikman's talk
  -- dipole models and CGC
  T. Lappi and C. Marquet's talks
Leading twist theory of nuclear shadowing

The leading twist theory of nuclear shadowing is an approach to calculate nuclear parton distributions (PDFs) as functions of $x$ and $b$ at some scale $Q_0^2$.

The $Q^2$ dependence is given by DGLAP.

The approach is based on:

- generalization of Gribov's theory of nuclear shadowing to DIS and to arbitrary nuclei
  Frankfurt and Strikman, '88 and '98

- collinear factorization theorem for inclusive and diffractive DIS
  J. Collins '98

- QCD fits to HERA measurement of diffraction in ep DIS
LT theory of nuclear shadowing-2

At high energies (small Bjorken $x$), the virtual photon interacts with many (all) nucleons of the nuclear target:

\[
F_{2A}(x, Q^2) = AF_{2N}(x, Q^2) - 8\pi A(A-1)\Re \frac{(1 - i\eta)^2}{1 + \eta^2} \int_{x}^{0.1} dx'_P F_2^{D(4)}(x, Q^2, x'_P, t_{\text{min}}) \\
\times \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1-z_2)x_P m_N}
\]

*In this formula, only the interaction with one and two nucleons

- $F_2^{D(4)}$ diffractive structure function
- $\rho_A$ nuclear density
- $\eta = ImA/ReA$
- $e^{i(z_1-z_2)x_P m_N}$ effect of coherence length
LT theory of nuclear shadowing-3

Use factorization theorem to replace the structure functions by the parton distributions:

\[
f_{j/A}(x, Q^2) = A f_{j/N}(x, Q^2) - 8\pi A(A - 1) \Re \left( \frac{(1 - i\eta)^2}{1 + \eta^2} \right) \int_{x_P}^{0.1} dx_P f_{j/N}^{D(4)}(x, Q^2, x_P, t_{\text{min}}) \\
\times \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1 - z_2)x_P} P^{mN}
\]
LT theory of nuclear shadowing-4

Model the interaction with $N \geq 3$ nucleons: color fluctuation approximation

$$xf_{j/A}(x, Q^2) = Axf_{j/N}(x, Q^2)$$

$$- xf_{j/N}(x, Q^2) 8\pi A (A - 1) \Re \left( \frac{(1 - i\eta)^2}{1 + \eta^2} \right) \int_0^{0.1} dx_{FP} \beta f_{D(3)}^j(\beta, Q^2, x_{FP})$$

$$\times \int d^2b \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\bar{b}, z_1) \rho_A(\bar{b}, z_2) e^{i(z_1 - z_2)x_{FP}m_\pi} e^{-\frac{1}{2}(1 - i\eta)\sigma_{soft}(x, Q^2) \int_{z_1}^{z_2} dz' \rho_A(\bar{b}, z')}$$

**Strong points:**
- NLO nuclear PDFs
- nuclear shadowing for indiv. flavor
- impact parameter dependent nuclear PDFs

(*Nuclear GPDs in the xi=0 limit*)
- same approach to nuclear diffractive PDFs

**Weak points:**
- modeling of multiple interactions
- significant uncertainty due to uncertainty in $B_{\text{diff}}$
- requires certain extrapolations of diffractive PDFs
- only vacuum channel (gluons and anti-q)
At the input scale, gluon shadowing $>\,$ quark shadowing

Antishadowing is by hand using momentum sum rule (compare to Kumano)

Shadowing for valence quarks from Eskola
Formalism of LT nuclear shadowing can be generalized to non-forward kinematics of DVCS and nuclear GPDs at small $x_B$


- The lower nuclear part is straightforward
- The upper part is difficult – we used a particular model
• Modeled double rescattering by DVCS on the “Pomeron”

• Used QCD factorization for DVCS to express DVCS amplitude in terms of GPDs

• Used light-cone coordinates to calculate the nuclear part
Final expression for nuclear GPDs in the presence of shadowing:

\[
H^j_A(x_N, \xi_A, t, Q^2) = F_A(t) \sum_N H^j_N(x_N, \xi_N, t, Q^2) \\
- \frac{A(A-1)}{2} 16\pi B_{\text{diff}} \Re \left\{ \int d^2 \bar{b} e^{i \vec{A}_1 \cdot \vec{b}} \int_\infty^\infty dz_1 \int_\infty^\infty dz_2 \int_{x_{IP}^{\text{min}}}^{0.1} dx_{IP} \right. \\
\times \rho_A(b, z_1) \rho_A(b, z_2) k_\eta e^{-i m_N z_2(x_B - 2\xi_N) + i m_N z_1 x_{IP}} e^{-\frac{A}{2}(1-i\eta)\sigma_{\text{eff}}(x_B, Q^2) \int_{z_1}^{z_2} dz' \rho_A(b', z')} \\
\times \phi_{IP/N}(x_{IP}) \phi_{IP/N}(x_{IP} - 2\xi_N) \left\{ \frac{1}{x_{IP}} H^j_{IP} \left( \frac{\xi_{IP}}{\xi_N}, x_N, \xi_{IP}, t_{\text{min}}, Q^2 \right) \right. \\
\left. \right\}.
\]

- This expression has correct forward limit – reproduces nuclear PDF
- In the $x_i=0$ limit, it is \textit{model-independent} and gives the impact parameter dependent nuclear PDFs (after the FT)
In the $\xi = 0$ limit, $t=-q^2$, and GPDs have the probabilistic interpretation in the impact parameter $b$ space.

$$R^q(x, b) = \frac{H_A^q(x, \xi = 0, b)}{A T_A(b) H_N^q(x, \xi = 0, b)}$$

**Density of nucleons at given $b$**

- Nuclear shadowing is larger at small $b$
- Nuclear shadowing introduces *correlations between $x$ and $b*$, even if such correlations are absent for the free nucleon GPDs
LT nuclear shadowing and nuclear GPDs-5

- Impact-parameter dependent nuclear shadowing leads to an **increase** of transverse size of partons (quarks and gluons) in nuclei

\[
\langle b_g^2 \rangle = \frac{\int d^2b b^2 g_A(x, Q^2, b)}{\int d^2b g_A(x, Q^2, b)}.
\]

\[
\langle b^2 \rangle_{\text{no shad}} = \frac{\int d^2b b^2 A T_A(b) f_{j/N}(x, Q^2)}{\int d^2b A T_A(b) f_{j/N}(x, Q^2)}
\]

- This has experimentally testable consequences:
  
  -- position of the minima of DVCS cross section shifts towards smaller \(t\)
  
  -- dramatic oscillations of DVCS asymmetries

---

Fig. 41. The ratio \(\langle b_g^2 \rangle/\langle b^2 \rangle_{\text{no shad}}\) for \(^{208}\text{Pb}\) as a function of Bjorken \(x\) at \(Q^2 = 4\) GeV

\[x\]
• The DVCS and BH cross sections for Pb-208 integrated over phi
The shift is the measure of nuclear shadowing
(In the example, $\Delta t=0.006$ GeV$^2$)

Similar pattern also for diffractive VM
production, H. Kovalski's talk

• The beam-spin DVCS asymmetry
The reason for the oscillations is shadowing,
position of nodes measures the strength
of shadowing
Summary

- Nuclear GPDs are interesting in their own right since they contain important and novel info on the 3D distribution of partons in nuclei and allow to study traditional and novel nuclear effects in off-diagonal kinematics (see my summary slide in Introduction).

- Out of these effects, off-diagonal EMC effect, nuclear shadowing and antishadowing (?) can be studied by an EIC.

  *JLab can also study off-diagonal EMC effect, but not shadowing

- Nuclear shadowing in nuclear DVCS and nuclear GPDs is large, and leads to an increase of transverse size of partons in nuclei which is measurable -- the shift of the minima of DVCS cross section and oscillations of DVCS asymmetries.