Medium modifications of bound nucleon generalized parton distributions

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INT-09-3 "Jefferson Laboratory Upgrade to 12 GeV"
INT, Seattle, October 30, 2009
Outline

• Introduction: why to study nuclear GPDs

• Coherent and incoherent nuclear DVCS
  – Hermes puzzle
  – new JLab measurement

• Incoherent nuclear DVCS and medium modifications of the bound nucleon GPDs
  – new JLab measurement
  – bound nucleon spin sum rule

• Conclusions
Introduction: Generalized parton distributions

- Deeply virtual Compton scattering (DVCS)
- Form factors
- Timelike Compton scattering
- Exclusive meson production, deep virtual/ large t
- 3D picture of hadrons, parton angular momentum
- Wide angle Compton scattering, $p\bar{p} \rightarrow \gamma\gamma$
- Parton distributions, DIS
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

“New” nuclear effects
- Medium modifications of bound nucleon GPDs
- Non-nucleon degrees of freedom
Papers on nuclear GPDs

- Theoretical description of nuclear GPDs requires GPDs of the (bound and off-shell) protons and neutrons as input
  VG and M. Strikman, PRC 68, 015204 (2003); VG, PRC 78, 025211 (2008);
  S. Scopetta, PRC 70, 015205 (2004) and PRC 79, 025207 (2009);
  S. Liuti and S.K. Taneja, PRC 72, 032201 (2005) and 034902 (2005)

- Incoherent DVCS on deuteron accesses almost-on-shell neutron GPDs
  M. Mazouz et al. (Hall A), PRL 99, 242501 (2007)

- Electro-production of pseudoscalar mesons on deuteron is sensitive to non-pole contribution to the GPD Etilde

- Electroproduction of pseudoscalar mesons on $^3$He at small $t$ probes GPDs of the neutron ($\gamma^*_L + ^3$He $\rightarrow \pi^0 + ^3$He) or proton ($\gamma^*_L + ^3$He $\rightarrow \pi^+ + ^3$H)
  L. Frankfurt et al., PRD 60, 014010 (1999)
Papers on nuclear GPDs-2

• Non-nucleon (meson) degrees of freedom

• Nuclear shadowing

• Medium modifications of bound nucleon GPDs

• Saturation and GPDs
  M.V.T. Machado, EPJ C 59, 769 (2009)
Nuclear DVCS

The cleanest process to study GPD is deeply virtual Compton scattering (DVCS).

Nuclear DVCS is more complex and versatile than DVCS on protons:

- many more final states can be excited
- targets with different spin and isospin
Coherent and incoherent nuclear DVCS

The theoretical analysis of nuclear DVCS is simplest when the final state is either elastic or complete set of states:

Coherent nuclear DVCS:
- dominates at small $t$
- cross sect. $\sim A^2 F_A^2(t)$
- JLab with 4He

Coherent and Incoherent nuclear DVCS:
- coh. dominates at small $t$, incoherent at large $t$
- cross sect. $\sim A^2 F_A^2(t)|T_A|^2 + A F_N^2(t)|T_N|^2$
- similar expression for BH and Interference
- Hermes measurement
Coherent and incoherent nuclear DVCS-2

Predictions for the ratio of the nuclear to proton beam-spin DVCS asymmetries, $A_{LU}^A/A_{LU}^p$, in Hermes kinematics, $x_B=0.065$, $Q^2=1.7\text{ GeV}^2$

VG and M. Strikman, PRC 68, 015204 (2003); VG, PRC 78, 025211 (2008)

- Enhancement at small $t$ is combinatoric:
  $$A_{LU}^A/A_{LU}^p \approx 1 + \frac{N}{Z} \frac{I_n}{I_p} \approx 1.65 - 1.85$$

- Suppression of incoh. DVCS at large $t$ is due to neutron

Coherent and incoherent nuclear DVCS-3

**Hermes 2006**

**Ratio** $A_{LU}^A/A_{LU}^P$ (Method 1)

- **Coherent enriched**: Mean ratio deviates from unity by $2\sigma$. Consistent with predictions between 1.8 and 1.95: Guzey/Strikman Phys.Rev.C 68 (2003)

- **Incoherent enriched**: Consistent with unity as naively expected

Frank Ellinghaus, University of Maryland, October 2006
Coherent and incoherent nuclear DVCS-4

Ratio of Leading BSA Amplitude: $A_{LU,A}^{(I),\sin \phi} / A_{LU,H}^{I,\sin \phi}$

- **Coherent enriched** (uncor. for smearing & acceptance, coherent fraction ~ 65%, except $^3$He~ 30%)
  - average value: $0.91 \pm 0.19$
  - $(t) = 0.018 \text{ GeV}^2$, $(x_B) = 0.065$, $(Q^2) = 1.70 \text{ GeV}^2$

- **Incoherent enriched** (uncor. for smearing & acceptance, elastic incoherent fraction ~ 60%)
  - average value: $0.93 \pm 0.23$
  - $(t) = 0.20 \text{ GeV}^2$, $(x_B) = 0.11$, $(Q^2) = 2.85 \text{ GeV}^2$

- The measured ratio of $A_{LU,A}^{(I),\sin \phi} / A_{LU,H}^{I,\sin \phi}$ is comparable with unity in both (in-)coherent enriched sample
- The results have been corrected for the background and other experimental effects, but not for the smearing (small effect, $\sim 0.01$) and acceptance effect
Possible sources of inconsistency

• **Experimental issues:**

  -- the final state is not detected, and the DVCS on proton could be overestimated (\(N \rightarrow \) Delta transition is included)?

• **Theoretical issues:**

  -- corrections due to nuclear binding in off-forward kinematics (“off-forward EMC effect”) are large
    S. Scopetta, PRC 79, 025207 (2009)

  -- strong medium modifications and off-shell effects
    S. Liuti and K. Taneja, PRC 72, 032201 and 034902 (2005)
Nuclear binding and nuclear GPDs

Traditional nuclear binding effects in nuclear GPDs can be taken into account using the impulse approximation, VG and M. Siddikov, 2006
S. Scopetta, 2004 and 2009

\[ H^q_A(x, \xi, t) = \sum_N \int_x^1 \frac{d\hat{z}}{\hat{z}} h^N_A(\hat{z}, \xi, t) H^q_N(\frac{x}{\hat{z}}, \frac{\xi}{\hat{z}}, t) \]

\[ \hat{z} = \frac{\vec{p}_N^+}{\vec{P}^+} \] LC fraction of the interacting nucleon

Off-diagonal light-cone distribution

Nucleon GPDs
Nuclear binding and nuclear GPDs-2

Calculations for $^3\text{He}$ using off-diagonal light-cone distribution $h_A$ obtained with off-diagonal spectral function and realistic NN potential

$$R_q(x, \xi, t) = \frac{H_{^3\text{He}}^q(x, \xi, t)}{H_{^3\text{He}}^{q,(0)}(x, \xi, t)}$$

S. Scopetta, PRC 79, 025207 (2009)

$$H_{^3\text{He}}^{q,(0)} = F_A(t)(2H_p^q + H_n^q)$$

“Off-diagonal EMC effect”

Forward EMC effect

$R_q(x_3, 0, 0)$

Solid: d quark; dashed: u quark
The new JLab experiment on DVCS on $^4\text{He}$

The new Jefferson Lab (CLAS) experiment on DVCS on $^4\text{He}$ may solve the Hermes “nuclear DVCS puzzle”.


The experiment will measure:

- purely coherent DVCS on $^4\text{He}$ (final nucleus detected with BoNuS)
- DVCS on the bound proton
The new JLab experiment on DVCS on $^4$He (2)

Coherent DVCS

Colored: Liuti and Taneja
Solid black: Guzey and Strikman

DVCS on bound $p$
Medium modifications of the bound nucleon

Properties of bound nucleons in a nuclear medium are expected to be modified:

- structure function \( F_{2N}^*(x,Q^2) \neq F_{2N}(x,Q^2) \) in DIS with nuclei (EMC effect)
- elastic form factors \( F_{1,2}^*(t) \neq F_{1,2}(t) \) in quasi-elastic scattering on nuclei
- recoil polarization in \( 4 He(e, e'p)^3 H \)

S. Strauch et al. [JLab Hall A] PRL 91, 052301 (2003); S. Malace at al, 0807.2252 [nucl-ex]

- axial coupling constant \( g_A^* < g_A \) in nuclear beta decay
- various static properties (masses, magnetic moments)

It is natural to expect that bound nucleon GPDs should also be modified by the nuclear medium.
Model for medium modifications of bound nucleon GPDs

Motivated by results on recoil polarization in quasi-elastic scattering on $^4$He that indicate that $F_{1,2}^*(t) \neq F_{1,2}(t)$, and by connection of GPDs and elastic form factors, we proposed a model for the bound nucleon GPDs.

V. Guzey, A.W. Thomas, K. Tsushima, PLB673 (2009) 9

**Results of Quark-Meson Coupling (QMC) model for bound proton in $^4$He**


Consistent with the data on recoil polarization in $^4He(e, e'p)^3H$
Incoherent nuclear DVCS on $^4$He

Beam-spin DVCS asymmetry for the bound proton:

$$A_{LU}(\phi) \propto \text{Im} \left( F_1^p \mathcal{H}_1^p - \frac{t}{4m^2_N} F_2^p \mathcal{E}_2^p \right) \Big/ \mathcal{F}(F_1^p, F_2^p) \sin \phi$$

suppression at small t since $F_1^*(t) < F_1(t)$

enhancement at large t since $F_2^*(t) > F_2(t)$
Incoherent nuclear DVCS on $^4$He (2)

- colored curves: S.Liuti, S.K.Taneja, PRC72, 032201 and 034902 (2005)

$x_B=0.238, Q^2=2 \text{ GeV}^2$

$x_B=0.132, Q^2=1.3 \text{ GeV}^2$
Medium modifications of bound nucleon GPDs lead to modifications of Ji's spin sum rule:

\[ J^q = \lim_{t, \xi \to 0} \frac{1}{2} \sum_q \int_{-1}^{1} dx \ x \left( H^q/N^* (x, \xi, t) + E^q/N^* (x, \xi, t) \right) \]

\[ > \lim_{t, \xi \to 0} \frac{1}{2} \sum_q \int_{-1}^{1} dx \ x \left( H^q/N (x, \xi, t) + E^q/N (x, \xi, t) \right) = J^q \]

\[ F_1^*(0) = F_1(0) \quad \text{and} \quad F_2^*(0) > F_2(0) \]

\[ J^q* > J^q \]

QMC for $^4\text{He}$, same trend for all nuclei.
Bound nucleon spin sum rule-2

- Separate $J^q$ into quark helicity $\Delta \Sigma$ and quark angular momentum $L^q$

$$\Delta \Sigma^* = \frac{1}{2} \sum_{q=u,d,s} \int_0^1 dx (\Delta q^*(x) + \Delta \bar{q}^*(x))$$

- In QMC model, the mechanism of suppression of the axial coupling constant, $g_A^* < g_A$, does not depend on isospin.

\[
g_A^* < g_A \quad \longrightarrow \quad \Delta \Sigma^* < \Delta \Sigma
\]

- Since $J^q^* > J^q$ and $\Delta \Sigma^* < \Delta \Sigma$ \quad \longrightarrow \quad $L^q^* > L^q$
All discussed medium modification effects are consequences of the enhancement of the lower component of the Dirac spinor for N field, i.e. of the relativistic treatment of the nuclear structure.

The large spin dependent EMC effect [I. Cloet et al, PLB 642, 210 (2006)] and the “reshuffling” of the nucleon spin to its orbital angular momentum [A.W.Thomas, PRL 101, 102003 (2008)] has the same origin!
Conclusions

• Nuclear GPDs are interesting because of the enhancement of the traditional nuclear effects (EMC effect, shadowing) and sensitivity to “new” nuclear effects (medium modifications), see my summary slide.

• The Hermes data on nuclear DVCS cannot be explained by simple models of nuclear DVCS -> need better calculations. The JLab experiment on $^4$He will measure coherent nuclear DVCS and will help to clarify the situation.

• One general ground, one expects that GPDs of the bound nucleon should be different from that of the free nucleon -> I presented a model motivated by the modification of the elastic form factors. The JLab experiment on $^4$He will clarify the situation.

• Modified GPDs lead to the modification of the Ji's spin sum rule for quarks: $\gamma_q^* \gamma_q^* > J_q^*$, $\Delta \Sigma^* < \Delta \Sigma$, $L_q^* > L_q$ which is a general property of relativistic nucleons.
Medium modifications the bound nucleon can be also probed in quasi-elastic scattering on nuclei.

Recent Jefferson Lab experiment measured proton recoil polarization in the reaction $^4\text{He}(\vec{e}, \vec{e}' \vec{p})^3\text{H}$

- The polarization transfer ratio measures the ratio of elastic form factors

$$\frac{P'_x}{P'_z} \propto \frac{G_E}{G_M}$$

- The super-ratio $R$ probes medium modifications of the bound elastic form factors

$$R = \frac{(P'_x/P'_z)^{^4\text{He}}}{(P'_x/P'_z)^{^1\text{H}}} = \frac{(G_E/G_M)^{^4\text{He}}}{(G_E/G_M)^{^1\text{H}}}$$
Can be explained either by
- medium modifications
or
- very strong charge-exchange FSI

However, very strong charge exchange FSI contradict induced polarization $P_y$