Nuclear medium modifications of bound nucleon generalized parton distributions

Vadim Guzey

Jefferson Laboratory

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Outline

• Introduction: A short review of nuclear medium modifications of properties of bound nucleons

• Bound nucleon generalized parton distributions and incoherent deeply virtual Compton scattering with nuclei
  
  V. Guzey, A.W. Thomas, K. Tsushima, PLB 673, 9 (2009)

• Medium modifications of the bound nucleon spin sum rule
  
  V. Guzey, A.W. Thomas, K. Tsushima, 0902.0780 [hep-ph]

• Summary
Nuclear modifications of bound nucleons

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 deep inelastic scattering with nuclear targets

- elastic form factors $F_1^*(t) \neq F_1(t)$ and $F_2^*(t) > F_2(t)$ in quasi-elastic scattering on nuclei

- axial coupling constant $g_A^* < g_A$ in nuclear beta decay

- various static properties (masses, magnetic moments)
DIS with nuclei: EMC effect

The story of medium modifications started with the EMC effect:

$$F_{2A}(x,Q^2) < AF_{2N}(x,Q^2) \text{ for } 0.7 > x > 0.2$$

European Muon Collaboration (EMC), CERN

Naive expectation: $F_{2A}(x,Q^2) = AF_{2N}(x,Q^2)$ since $Q^2 \gg$ nuclear scales
Interpretation of EMC effect

The EMC effect cannot be explained by assuming that the nucleus consists of unmodified nucleons

\[
\frac{1}{A} F_{2A}(x) = \int_x^A dy f_N(y) F_{2N}^*(\frac{x}{y})
\]

\[
y = A \frac{k^+}{p^+_A}
\]

is the light-cone fraction of the nucleus carried by the nucleon

\[
f_N(y)
\]

is the probability to find the nucleon with given \( y \)
Interpretation of EMC effect

\[ f_N(y) \text{ is peaked around } y \approx 1 \]

\[ \frac{1}{A} F_{2A}(x) = F_{2N}^*(x) + \frac{\langle T \rangle}{3m_N} \left( 2xF_{2N}^*(x) + x^2F_{2N}^{*''} \right) \]

Assuming that \( F_{2N}^*(x) = F_{2N}(x) \)

An explanation of the EMC effect requires either

1) medium modifications, \( F_{2N}^*(x,Q^2) \neq F_{2N}(x,Q^2) \),
   

2) explicit non-nucleonic degrees of freedom (pion excess models)
   
Interpretation of EMC effect

A particular realization of $F_{2N}^*(x,Q^2) \neq F_{2N}(x,Q^2)$ is the Quark-Meson coupling model,

QMC model:
• nucleus=collection of non-overlapping nucleon bags

• quarks in the bags interact with the scalar and vector fields, which provide nuclear binding

• coupling constants tuned to reproduce properties of nuclear matter

Successful description of nuclear structure (level structure, charge form factors, binding energies, etc.)
Interpretation of EMC effect

QMC model semi-quantitatively explains the EMC effect

Quasi-elastic scattering

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 $^4\text{He}(\overrightarrow{e},e'\overrightarrow{p})^3\text{H}$.

- 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 $R = \frac{(P'_x/P'_z)^{^4\text{He}}}{(P'_x/P'_z)^{^1\text{H}}} = \frac{(G_E/G_M)^{^4\text{He}}}{(G_E/G_M)^{^1\text{H}}}$.

S. Malace et al., 0807.2252 [nucl-ex]
Quasi-elastic scattering

S. Malace at al, 0807.2252 [nucl-ex]

Can be explained either by

- medium modifications
- or
- very strong charge-exchange FSI

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

Generalized parton distributions (GPDs) interpolate between parton distributions and form factors

\[ \int_{-1}^{1} dx H^q(x, \xi, t) = F_1^q(t) \]

\[ \int_{-1}^{1} dx E^q(x, \xi, t) = F_2^q(t) \]

GPDs of the bound nucleon should also be modified by the nuclear medium.
Bound nucleon GPDs

Natural model for GPDs of the bound nucleon:
V. Guzey, A.W. Thomas, K. Tsushima, PLB 673, 9 (2009)

\[
H^{q/N^*}(x, \xi, t) = \frac{F_1^{q/N^*}(t)}{F_1^{q/N}(t)} H^{q/N}(x, \xi, t)
\]

\[
E^{q/N^*}(x, \xi, t) = \frac{F_2^{q/N^*}(t)}{F_2^{q/N}(t)} E^{q/N}(x, \xi, t)
\]

Double distribution model for GPDs,
M. Guidal et al, PRD 72, 054013 (2005)

QMC for $^4\text{He}$
Incoherent nuclear DVCS

GPDs of the bound nucleon can be probed in incoherent deeply virtual Compton scattering (DVCS) with nuclear targets

Ignoring Fermi motion:

\[ |T_{DVCS}^{\text{He}}|^2 = \sum_\lambda |T_{DVCS}^{p^*}|^2 \]
Incoherent nuclear DVCS

DVCS interferes with Bethe-Heitler (BH) process

In fixed-target kinematics, BH \(\gg\) DVCS. One extracts information on DVCS and GPDs by measuring cross section asymmetries, which are proportional to the interference between DVCS and BH.

Beam-spin asymmetry (polarized beam)

\[
A_{LU}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin \phi F_1(t) \text{Im} \mathcal{H}
\]
Incoherent nuclear DVCS on $^4$He

\[ A_{LU}(\phi) \propto \text{Im} \left( F_1^p H^p - \frac{t}{4m_N^2} F_2^p E^p \right) / f(F_1^p, F_2^p) \sin \phi \]

- will be tested by the approved JLab at 6 GeV experiment
  

- our predictions are very different from the only other existing model
  
  S.Liuti, S.K.Taneja, PRC72, 032201 and 034902 (2005)

\[ A_{LU}^{P^\prime}/A_{LU}^P \]

\[ E = 6 \text{ GeV} \]

\[ Q^2 = 2 \text{ GeV}^2, \phi = \pi/2 \]

V.Guzey, A.W. Thomas, K. Tsushima, PLB 673, 9 (2009)
Bound nucleon spin sum rule

Medium modifications of bound nucleon GPDs lead to modifications of Ji's spin sum rule

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

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

\[
F_1^*(0) = F_1(0)
\]

\[
F_2^*(0) > F_2(0)
\]

QMC for $^4\text{He}$

QMC for $^4\text{He}$
Bound nucleon spin sum rule

- 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.

\[
g_A^* < g_A \implies \Delta \Sigma^* < \Delta \Sigma
\]

- Since $J^{q^*} > J^q$ and $\Delta \Sigma^* < \Delta \Sigma \implies L^{q^*} > L^q$
Bound nucleon spin sum rule

V. Guzey, A.W. Thomas, K. Tsushima, 0902.0780 [hep-ph]
Conclusions

• On very general grounds one expects that GPDs of the bound nucleon should be different from that of the free nucleon.

• Assuming that bound nucleon GPDs are modified in proportion to the corresponding elastic form factors, as predicted by QMC, we calculate beam-spin asymmetry in incoherent DVCS on $^4$He.

• The deviation from the free proton case is as large as 6%, will be tested by a dedicated JLab experiment.

• Modified GPDs lead to the modification of the Ji's spin sum rule for quarks: $J^q > J^q$, $\Delta \Sigma^* < \Delta \Sigma$, $L^q > L^q$

Can be explained by the enhancement of lower component of the quark spinor in nuclear medium.