Search for Proton Medium Modifications in the $^4$He(e,e'p) Reaction

Steffen Strauch
University of South Carolina

NuInt07: Fifth International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region
May 30, 2007 - June 3, 2007, Fermilab, Batavia, Illinois USA
Motivation

• Accurate description of $A(e,e')$ data sets strong restrictions on nuclear models of neutrino reactions, $A(\nu_i, I^-)$

• Nuclear reaction-model ingredients:
  ▶ Relativity
  ▶ Final-state interactions
  ▶ Medium modifications
  ▶ ...

• Exclusive $A(e,e'p)$ data provide for additional, sensitive tests
  ▶ Cross sections
  ▶ Polarization observables

e.g., O. Benhar et al., Phys. Rev. D 72, 053005 (2005); J.E. Amaro et al., Phys. Rev. C 75, 034613 (2007); K. Tsushima, H. Kim, K. Saito, Phys. Rev. C 70, 038501 (2004)
Outline

• Electron-nucleus scattering
  ▶ Example model: Relativistic distorted-wave impulse approximation (RDWIA)
• Nucleons in the nuclear medium
  ▶ Example model: Quark meson coupling model (QMC)
• Experimental results
  ▶ Polarization-transfer technique
  ▶ $^1$H(e,e’p) : Free proton electromagnetic form factors
  ▶ $^4$He(e,e’p) : Search for proton medium modifications
• Summary
Quasielastic Scattering from Bound Nucleons

\[ J_{\mu}^{N}(\omega, \bar{q}) = \int d\bar{p} \, \bar{\psi}_F(\bar{p} + \bar{q}) \hat{J}_{\mu}^{N}(\omega, \bar{q}) \psi_B(\bar{p}) \]

- Relativistic \( \psi_B \) and \( \psi_F \) wave functions for initial bound and final outgoing nucleons, respectively.
- Relativistic nucleon current operator of cc1 or cc2 forms

\[ \hat{J}_{\mu}^{N}(cc1) = (F_1 + \kappa F_2)\gamma^\mu - \frac{\kappa F_2}{2M} (P_F + \bar{P}_I)^\mu \]

(possible medium-modified form factors enter here)

J.M. Udias et al., Phys. Rev. Lett. 83, 5451 (1999)
Excellent Description of Many Observables

$^{16}\text{O}(e,e'p)$ at $Q^2 = 0.8 \ (\text{GeV/c})^2$

- Importance of fully relativistic calculation; here, particularly, the bound-state spinor distortion
- Also excellent description of $^{12}\text{C}(e,e'p)$ induced polarization.

J. Gao et al., Phys. Rev. Lett. 84, 3265 (2000); J.M. Udias et al., Phys. Rev. Lett. 83, 5451 (1999)
Nucleon in the Nuclear Medium

QCD vs. conventional Nuclear Physics

• Conventional Nuclear Physics:
  Nucleons are effectively and well described as
  ► point-like protons and neutrons (+ form factor)
  ► interaction through effective forces (meson exchange)

• Underlying theory: QCD
  ► Nucleons and mesons are not the fundamental entities
  ► In the chiral limit, phase transition to quark-gluon plasma

P.A.M. Guichon and A.W. Thomas, Phys. Rev. Lett. 93, 132502 (2004)
The EMC Effect

• Depletion of the nuclear structure function $F_2^A(x)$ in the valence-quark regime $0.3 \leq x \leq 0.8$

• J. Smith and G. Miller: chiral quark-soliton model of the nucleon
  Conventional nuclear physics does not explain EMC effect

$R(x, Q^2) = F_2^A / AF_2^N$

• Nucleon structure is modified in the nuclear medium

SLAC-E139 data for Iron and Gold;
Figure from Jason R. Smith and Gerald A. Miller, Phys. Rev. Lett. 91, 212301 (2003)
Limits for Medium Modifications

• Best constraints from $y$-scaling
  ▶ $Q^2 > 1 \text{ (GeV/c)}^2$, $\Delta G_M < 3\%$ [1]

• Coulomb Sum Rule, L-Response
  ▶ No quenching in the data observed [2]
  ▶ Quenching of $S_L$ is experimentally established [3]
  ▶ $Q^2 \leq 0.5 \text{ (GeV/c)}^2$: $\Delta G_E < 15\%$ or even $< 5\%$

• Exclusive $A(e,e'p)$ processes
  ▶ LT Separation

[1] I. Sick, in: H. Klapdor (Ed.), Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei, Springer-Verlag, Berlin, 1986, p. 415
[2] J. Jourdan, Nucl. Phys. A 603, 117 (1996), J. Carlson et al., Phys. Lett. B 553, 191 (2003)
[3] J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)
Quark Meson Coupling Model (QMC)

- Structure of the nucleon described by valence quarks in a bag (Cloudy-bag model).

- Nuclear system described using effective scalar ($\sigma$) and vector ($\omega$) meson fields.

- Scalar and vector fields of nuclear matter couple directly to confined quarks.

$\rightarrow$ Modification of internal structure of bound nucleon

**QMC:** D.H. Lu, A.W. Thomas, K. Tsushima, A.G. Williams, K. Saito, Phys. Lett. B 417, 217 (1998); D.H. Lu et al., Phys. Rev. C 60, 068201 (1999); **Other models:** e.g.: J.R. Smith and G.A. Miller, Phys. Rev. C 70, 065205 (2004); T. Horikawa, W. Bentz, Nucl. Phys. A 762, 102 (2005)
Bound Proton EM Form Factors

- Electromagnetic rms radii and magnetic moments of the bound proton are increased.
- **Charge form factor** much more sensitive to the nuclear medium than the **magnetic** ones.

D.H. Lu et al., Phys. Rev. C 60, 068201 (1999)
Effect on charged-current $\nu$-A scattering

QMC bound nucleon form factors of vector and axial-vector currents

- Tsushima et al. compute the inclusive $^{12}\text{C}(\nu_\mu, \mu^-)X$ cross sections using a relativistic Fermi gas model with the calculated bound nucleon form factors.

- The effect of the bound nucleon form factors for this reaction is a reduction of 8% for the total cross section, relative to that calculated with the free nucleon form factors.

K. Tsushima, Hungchong Kim, and K. Saito, Phys. Rev. C 70, 038501 (2004)
Polarization-Transfer Technique

- Free electron-nucleon scattering

\[ \frac{G_E}{G_M} = -\frac{P'_x}{P'_z} \cdot \frac{(E_i + E_f)}{2m} \tan \left( \frac{\theta_e}{2} \right) \]

- Bound nucleons → evaluation within model

Reaction-mechanism effects in \( A(e', e'p)B \) predicted to be small and minimal for

- Quasielastic scattering
- Low missing momentum
- Symmetry about \( p_m = 0 \)

R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C 23, 363 (1981); for reaction-mechanism effects, e.g., J.M. Laget, Nucl. Phys. A 579, 333 (1994), J.J. Kelly, Phys. Rev. C 59, 3256 (1999), A. Meucci, C. Guisti, and F.D. Pacati, Phys. Rev. C 66, 034610 (2002).
Proton Elastic Form-Factor Ratio

- Systematic decrease of $G_E / G_M$ indicating difference in spatial distribution of charge and magnetization currents in the proton.

Figure from: I.A. Qattan, Phys. Rev. Lett. 94, 142301 (2005)
Proton Charge and Magnetization Densities

Parameterization of nucleon e.m. form factors based upon radial densities

- Proton charge density is broader than magnetization density

\[ \langle r_E^2 \rangle > \frac{1}{\mu_p} \langle r_M^2 \rangle \]

- Consistent with polarizabilities

\[ \alpha_E > \beta_M \]

J.J. Kelly, Phys. Rev. C 66, 065203 (2002)
S. Kondratyuk, K. Kubodera, and F. Myhrer, Phys. Rev. C 71, 028201 (2005)
Thomas Jefferson National Accelerator Facility

- Electron-beam accelerator
- Polarized electron beam
- Beam energies up to $E_0 = 6 \text{ GeV}$
- Three experimental Halls A, B, and C

JLab in Newport News, VA
E93-049 and E03-104 at Jefferson Lab Hall A

\[ ^4\text{He}(e, e' \vec{p})^3\text{H} \quad \text{in quasielastic kinematics } Q^2 = 0.5 - 2.6 \ (\text{GeV/c})^2 \]

- Polarization-transfer ratio \( P'_x/P'_z \): sensitive to \( G_E/G_M \)
- Induced polarization \( P_y \): sensitive to final-state interactions

\[ \text{Proton arm with Focal Plane Polarimeter} \]

\[ \text{Electron arm} \]

\[ \text{Polarized Electron Beam } \quad E_0 = 2 - 4 \ \text{GeV} \]

\[ \text{Target Chamber: } ^1\text{H and } ^4\text{He targets} \]

S. Dieterich, et al., Phys. Lett. B500, 47(2001); S. Strauch, et al., Phys. Rev. Lett. 91, 052301(2003); JLab E03-104, R.Ent, R. Ransome, S. Strauch, P. Ulmer (spokespersons)
Polarization Measurement

Observed angular distribution

\[
I(\vartheta, \varphi) = I_0(\vartheta) \left( 1 + \epsilon_y \cos \varphi + \epsilon_x \sin \varphi \right)
\]

\[
= I_0(\vartheta) \left[ 1 + AC(P_y \cos \varphi - P_x \sin \varphi) \right]
\]
Free Proton Form-Factor Ratio $G_E/G_M$

- Preliminary results from E03-104 with small statistical uncertainties 
  $\delta(P'_x/P'_z) \approx 0.7 \%$
$^4\text{He}(\vec{e}, e' \vec{p})$ - Polarization-Transfer Ratio

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

- RDWIA and RMSGA models can not describe the data.

RDWIA: J.M. Udias et al., Phys. Rev. Lett. 83, 5451 (1999);
RMSGA: P. Lava et al., Phys. Rev. C 71, 014605 (2005), D. Debruyne et al., Phys. Rev. C 62, 024611 (2000)
$^4\text{He} (\vec{e}, e' \vec{p})$ - Polarization-Transfer Ratio

$Q^2 = 1.0 \text{ (GeV/c)}^2$

- $R_{RDWIA} \approx 0.97 \times R_{RPWIA}$
- Small sensitivity to
  - bound-state wave function
  - current operator
  - optical potential
- Enhancement of lower components (spinor distortions) in RDWIA
Limited Role of MEC in $^4\text{He}(e,e'p)^3\text{H}$

Relativistic mean-field calculation: A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C 66, 034610 (2002)
Spin-Dependent Charge-Exchange FSI

- $R$ suppressed by about 4% from MEC
- Spin-dependent charge exchange FSI suppresses $R$ by about 6%
- CH-EX term not well constrained ⇒ need $P_y$ from E03-104

RDWIA: J.M. Udias et al., Phys. Rev. Lett. 83, 5451 (1999)
RMSGA: P. Lava et al., Phys. Rev. C 71, 014605 (2005), D. Debruyne et al., Phys. Rev. C 62, 024611 (2000)
R. Schiavilla et al., Phys. Rev. Lett. 94, 072303 (2005)
Induced Polarization in $^4\text{He}(e,e' \vec{p})$

- $P_y$ is a measure of final-state interactions

- Final-state interactions small, RDWIA results consistent with data
- Need smaller systematic uncertainties from E03-104 to constrain models

R. Schiavilla et al., Phys. Rev. Lett. 94, 072303 (2005)
In-Medium Form Factors

\[ G_{E,M}(Q^2, \rho) = \frac{G_{E,M}^{QMC}(Q^2, \rho)}{G_{E,M}^{QMC}(Q^2, 0)} G_{E,M}^{\text{free}}(Q^2) \]

- Data effectively described by proton medium modified form factors
- New data set additional tight constraints
Summary

• Proton in the nuclear medium
  ► Models (like Quark Meson Coupling) predict change of the internal structure of a bound nucleon
  ► Corrections due to in-medium form factors (electromagnetic, axial) could be significant

• Polarization transfer in $^4$He(e,e’p)
  ► Significant deviation from RDWIA results; data effectively described by proton medium modifications
  ► Alternative interpretation in terms of strong charge-exchange FSI
  ► Induced polarization crucial to clarify role of FSI
  ► New results from E03-104 will provide needed constraints