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

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Outline

• Nucleon medium modifications
  ▶ Signatures and experimental limits
  ▶ Models for in-medium form factors
• Results from JLab $^4$He(e,e’p) experiments
  ▶ Polarization-transfer technique
  ▶ Competing interpretations of previous data from E93-049
  ▶ New constraints from preliminary data* from E03-104
• Possible new experiment in Hall C
• Summary

*Simona Malace (USC postdoc) and Michael Paolone (USC grad. student)
Nucleon in the Nuclear Medium

• Conventional Nuclear Physics:
  ► Nuclei are effectively and well described as point-like protons and neutrons (+ form factor) and interaction through effective forces (meson exchange)
  ► **Medium effects** arise through non-nucleonic degrees of freedom

• Nucleon Medium Modifications:
  ► Nucleons and mesons are not the fundamental entities in QCD
  ► In the chiral limit, phase transition to quark-gluon plasma
  ► **Medium effects** arise through changes of fundamental properties of the nucleon
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

\[ R(x, Q^2) = \frac{F_2^A}{AF_2^N} \]

\[ \text{SLAC-E139 data for Iron and Gold} \]

- Nucleon structure is modified in the nuclear medium
- Note: prelim. E03-103 $^4$He data consistent with SLAC A=12 param.

Dave Gaskell, NuINT07, May 31 2007
Limits for Medium Modifications

• Best constraints from $y$-scaling
  - $Q^2 > 1$ (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]
  - Good agreement between theory and experiment for $^4$He when using free-nucleon form factors [4]
  - $Q^2 \leq 0.5$ (GeV/c)$^2$: $\Delta G_E < 15\%$ or even $< 5\%$

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.

→ Modification of internal structure of bound nucleon

Bound Proton EM Form Factors

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

Chiral Quark Soliton Model (CQSM)

- **Chiral-soliton model** provides the quark and antiquark substructure of the proton, embedded in nuclear matter.
- **Medium modifications:**
  - significant for the ratio $G_E/G_M$
  - no strong enhancement of the magnetic moment

Extended Skyrme Model

- Model of the nucleon based on Skyrme Lagrangian
- Results comparable to QMC, but differ in details
- \( \frac{G_E}{G_M}_{\text{medium}} / \frac{G_E}{G_M}_{\text{free}} \approx 1 \) for \( R = 1 \) fm

Other Models

• **Nambu–Jona-Lasinio model**
  ► Nucleon as quark-diquark bound state + nuclear matter in the mean field approximation.
  ► Medium modifications: increase of the electric size in the medium
  ► **Medium modifications decrease with increasing** $Q^2$ **for both**, spin and orbital form factors.

• **S. Liuti**
  ► Connection between the modifications induced by the nuclear medium of the nucleon form factors and of the deep inelastic structure functions, obtained using the concept of generalized parton distributions.
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

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

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

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.
- Discrepancy can possibly be resolved by the inclusion of two photon effects in the Rosenbluth analysis.

I.A. Qattan, Phys. Rev. Lett. 94, 142301 (2005); Hall A E01-001
E93-049 and E03-104 at Jefferson Lab Hall A

$^4$He($e, e' p$)$^3$H 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

Polarization Measurement

Focal-Plane Polarimeter

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 $\delta(P'x/P'z) \approx 0.7\%$
- Full analysis of E03-104 will have reduced systematic uncertainties
$^4\text{He}(\bar{e}, e' p)$ - Polarization-Transfer Ratio

$$R = \frac{P_x'/P_z'(^4\text{He})}{P_x'/P_z'(^1\text{H})}$$

- RDWIA and RMSGA models cannot describe the data.
- New data will set tight constraints

\( ^4\text{He}(\vec{e}, e' \vec{p}) \) - Polarization-Transfer Ratio

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

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

- Previous data effectively described by proton medium modified form factors
- Preliminary data from E03-104 possibly hint at an unexpected trend in $Q^2$.

Inner uncertainties are statistical only; full analysis of E03-104 will have reduced systematic uncertainties.

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Charge-Exchange FSI

- $R$ suppressed by about 4% from MEC
- Spin-dependent charge exchange FSI suppresses $R$ by about 6% and provides for alternative explanation
- CH-EX term not well constrained $\Rightarrow$ need $P_y$ from E03-104

Induced Polarization in $^4\text{He}(e,e' \bar{p})$

- $P_y$ is a measure of final-state interactions
- Observed final-state interactions are small and increase with missing momentum
- RDWIA results consistent with data
- RDWIA can be used to correct data for HRS acceptance (30% - 40% effect)

E03-104 induced polarization still very preliminary. Uncertainties are statistical only; systematic uncertainties < 0.02
Induced Polarization in $^4\text{He}(e, e' \bar{p})$

- Observed final-state interaction small and with very weak $Q^2$ dependence
- RDWIA results consistent with data
- Spin-dependent charge exchange terms not constrained by N-N scattering and possibly overestimated
- E03-104 took specific data that will set tight constraints on FSI

Inner uncertainties are statistical only; full analysis of E03-104 will have reduced systematic uncertainties
New Proposal to Measure $^4\text{He}(e,e'p)^3\text{H}$ in Hall C

- Proton spectrometer: HMS
  Electron spectrometer: SOS (momentum bite: 40%)
- HMS is being equipped with FPP for $G_E^p$-III
- Missing mass resolution sufficient to identify $^3\text{H}$ in the final state if SOS is used as electron spectrometer.

E. Brash, G. Huber, S. Strauch
Q^2 Distribution of R

- Anticipated data in 27 days of beam time on ^4He
Improved constraints on models through missing-momentum distribution

“Would be nice to study modification of the nucleon form factors as a function of the nucleon momentum.” [Mark Strikman]
Proposed Hall C data: induced polarization
Summary

• **Proton in the nuclear medium**
  - Models predict change of the internal structure of a bound nucleon
  - Corrections due to in-medium form factors could be significant

• **Polarization transfer in \( ^4\text{He}(e,e'p) \)**
  - 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
  - Experiment in Hall C could measure missing-momentum distributions and extend the data set to larger \( Q^2 \)