Medium Modifications from $^4\text{He}(e,e'p)^3\text{H}$

- Nucleons in the Nuclear Medium and in-medium electromagnetic form factors
- Preliminary results from JLab experiment E03-104 (Hall A Collaboration)
  - Polarization transfer
  - Induced polarization
- Momentum dependence of bound nucleon wave function

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Nucleons 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.
  ➤ Are free nucleons and mesons, under every circumstance, the best quasi-particle to chose?

• Nucleon Medium Modifications:
  ➤ Nucleons and mesons are not the fundamental entities in QCD.
  ➤ Medium effects arise through changes of fundamental properties of the nucleon.
  ➤ Do nucleons change their quark-gluon structure in the nuclear medium?
The EMC Effect

- The European Muon Collaboration used muon scattering to measure nuclear structure functions and observed a 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.

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

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
y - Scaling Function

- y - scaling analysis of quasielastic scattering data
- Deviation of the cross-section from scattering from free nucleons scales to a function of a single variable y, the longitudinal momentum distribution.
- y-scaling property very sensitive to change of nucleon radius
- Limits: $Q^2 > 1 \text{ (GeV/c)}^2 : \Delta G_M < 3\%$

$I.\: Sick,\: D.\: Day\: and\: J.S.\: McCarthy,\: Phys.\: Rev.\: Lett.\: 45,\: 871\: (1980);$
Limit on radius from I. Sick, in: H. Klapdor (Ed.), Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei, Springer-Verlag, Berlin, 1986, p. 415

\[
F(y) = \frac{\sigma(q, \omega)}{Z\sigma_{ep} + N\sigma_{en}} \cdot \frac{d\omega}{dy}
\]
Coulomb Sum Rule

• **CSR:** Integral of the quasi-elastic electric response Response $R_L(q, \omega)$

\[
S_L(q) = \frac{1}{Z} \int_{\omega^+}^{\infty} \frac{R_L(q, \omega)}{\tilde{G}_E^2} d\omega \rightarrow 1
\]

• Experimental findings controversial:
  - 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]

• Limits: $Q^2 \leq 0.5 \text{ (GeV/c)}^2$
  - $\Delta G_E < 15\%$ or even $< 5\%$

• New data expected from JLab E05-110
  [Choi, Chen, and Meziani]

[1] I. Sick, Phys. Lett. B 157, 13 (1985)
[2] J. Jourdan, Nucl. Phys. A 603, 117 (1996)
[3] J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)
[4] J. Carlson, J. Jourdan, R. Schiavilla, and I. Sick, Phys. Lett. B 553, 191 (2003)
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

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)
Electromagnetic rms radii and magnetic moments of the bound proton are increased.

At low $Q^2$: 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)
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 $G_E$, only moderate for $G_M$
  - no strong enhancement of the magnetic moment

CQSM: J.R. Smith and G.A. Miller, Phys. Rev. C 70, 065205 (2004)
Other Models

• **Extended Skyrme Model**
  U. Yakhshiev, U. Meißner, A. Wirzba, Eur. Phys. J. A 16, 569 (2003)
  - Model of the nucleon based on Skyrme Lagrangian
  - Results for $^4$He comparable to QMC, but differ in detail
  - $(G_E/G_M)_{\text{medium}}/(G_E/G_M)_{\text{free}} \approx 1$ for $R = 1$ fm

• **Nambu–Jona-Lasinio model**
  T. Horikawa, W. Bentz, Nucl. Phys. A 762, 102 (2005)
  - 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.

• **Generalized Parton Distributions**
  S. Liuti, hep-ph/0608251, hep-ph/0601125
  - 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.
Medium-modified form factors are not an experimental observable. How can we test these predictions?

Strategy:

• Choose an observable with high sensitivity to nucleon structure while being at the same time least sensitive to conventional medium effects.

• Chose a dense yet simple nuclear target, which allows for microscopic calculations.

• Provide high-precision data to put Nuclear Physics models to rigorous test.
Polarization-Transfer Technique

• Free electron-nucleon scattering

\[
\frac{G_E}{G_M} = -\frac{P'_x}{P'_z} \cdot \frac{E_i + E_f}{2m} \tan \left( \frac{\theta_e}{2} \right) 1^1H(\vec{e}, \vec{e}' \vec{p})
\]

• Bound nucleons → evaluation within model

Reaction-mechanism effects predicted to be small and minimal for

- Quasielastic scattering
- Small missing momenta
- 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 Recoil Polarization in $^4\text{He}(\vec{e}, e' \vec{p})^3\text{H}$

- **Kinematics**: low missing momentum, quasielastic scattering

- **Channel identification by missing mass** (Mike Paolone)

- **Polarization-transfer ratio** $P'_x/P'_z$: sensitive to $G_E/G_M$

$$R = \left( \frac{P'_x}{P'_z} \right)_{\text{bound}} \bigg/ \left( \frac{P'_x}{P'_z} \right)_{\text{free}}$$

- **Induced polarization** $P_y$: sensitive to final-state interactions
Thomas Jefferson
National Accelerator Facility

JLab in Newport News, VA

Hall A Counting House
E93-049 and E03-104 at Jefferson Lab Hall A

$^4\text{He}(e,e'p)^3\text{H}$ in quasielastic kinematics $Q^2 = 0.5 – 2.6$ (GeV/c)$^2$

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

Spin-dependent scattering

\[ \vec{l} \cdot \vec{s} < 0 \quad \text{Left / right asymmetry} \quad \vec{l} \cdot \vec{s} > 0 \]

Observed angular distribution

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

\[
= I_0(\theta) \left[ 1 + A_C(P_y \cos \varphi - P_x \sin \varphi) \right]
\]
Observed Angular Distribution

- Excellent control of systematic uncertainties for polarization transfer
- Instrumental asymmetries complicate the extraction of induced polarization
  - Detector misalignment
  - Detector inefficiencies
  - Tracking problems

(Simona Malace)

E03-104, preliminary

\[
\frac{1}{2I_0} \left[ I(h=+1) + I(h=-1) \right]
\]

\[
\frac{1}{I(h=+1) - I(h=-1)}
\]

\[
\left( ^1\text{H}(e,e'p) \right)
\]

\[
Q^2 = 0.8 \text{ GeV}^2
\]

Helicity Difference

Helicity Sum

no asymmetry expected for \(^1\text{H}\) (one photon approx.)

\[
\phi_{\text{FPF}} \text{ (deg)}
\]
Free Proton Form-Factor Ratio $\mu_p G_E/G_M$

- Preliminary results from E03-104 in good agreement with previous data.
- Small statistical uncertainties 0.7% from E03-104.
- Final data will have reduced systematic uncertainties.

$\mu_p(G_E^p/G_M^p)$

$Q^2$ (GeV/c)$^2$

new data

- B. Milbrath et al., PRL 82, 2221 (1999)
- M.K. Jones et al., PRL 84, 1398 (2000)
- O. Gayou et al., PRC 64, 038202 (2001)
- S. Dieterich et al., PLB 500, 47 (2001)
- S. Crawford et al. PRL 98, 052301 (2007)
- G. Ron et al. PRL 99, 202007 (2007)
- JLab E93-049, E03-104 (preliminary)
$^2$H and $^4$He(e,e’p) Polarization-Transfer Ratios

- $^2$H and $^1$H polarization-transfer data are similar.
- $^4$He data are significantly different than $^2$H, $^1$H data.
- Small effect for less dense nucleus, larger for denser.
- RDWIA and RMSGA models cannot describe $^4$He data.

$$R = \left( \frac{P'^x}{P'^z} \right)_{\text{bound}} / \left( \frac{P'^x}{P'^z} \right)_{\text{free}}$$

$^2$H Model: H. Arenövel; see: B. Hu et al., Phys. Rev. C 73, 064004 (2006).
RDWIA: J.M. Udias et al., Phys. Rev. Lett. 83, 5451 (1999).
Relativistic Multiple-Scattering Glauber Approximation (RMSGA): P. Lava et al., Phys. Rev. C 71, 014605 (2005), D. Debruyne et al., Phys. Rev. C 62, 024611 (2000).
\(^4\text{He}(e,e'p)^3\text{H} - \text{Polarization-Transfer Ratio}\)

- Previous and preliminary high-statistics data from E03-104 are also low compared to RDWIA.
- \(R^{\text{RDWIA}}\) reduced by 3\% compared to \(R^{\text{RPWIA}}\) due to Enhancement of lower components (spinor distortions) in RDWIA.
- Small sensitivity to
  - bound-state wave function
  - current operator
  - optical potential (not including charge exchange terms)
Role of MEC in $^4\text{He}(e,e'p)^3\text{H}$

- The seagull diagram effects generally small and visible only at high missing momenta; MEC expected to give more significant effect in the induced polarization
  
  Relativistic mean-field calculation: A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C 66, 034610 (2002)

- $R$ is suppressed by about 4% with respect to that obtained with one-body currents only
  
  R. Schiavilla, O. Benhar, A. Kievsky, L.E. Marcucci, and M. Viviani, Phys. Rev. Lett. 94, 072303 (2005)
Polarization Transfer in $^4\text{He}(\bar{e}, e' \bar{p})^3\text{H}$

\[ G(Q^2, \rho) = G(Q^2) \frac{G_{\text{QMC}}(Q^2, \rho)}{G_{\text{QMC}}(Q^2)} \]

- In-medium form factors: density-dependent form factors are evaluated at the local density $\rho(r)$.
- $R$ is reduced by an additional 6% (QMC).
- Data effectively described by proton medium modified form factors.
Interpretation of Polarization-Transfer Data

- Data consistent with:
  - RDWIA
  - Density-dependent medium modified form factors.

  OR

  - Free form factors
  - MEC
  - Spin-dependent charge-exchange FSI (not well constrained ⇒ need \( P_y \) from E03-104)

R. Schiavilla, O. Benhar, A. Kievsky, L.E. Marcucci, and M. Viviani, Phys. Rev. Lett. 94, 072303 (2005)

- The modeling of final-state interactions can be tested by measuring the induced polarization, \( P_y \).
Induced Polarization in $^4\text{He}(e,e'\bar{p})$

- $P_y$ is a measure of final-state interactions (FSI).
- $P_y$ is insensitive to in-medium form factors.
- Observed final-state interaction small and with only very weak $Q^2$ dependence.
- Results from RDWIA and Laget consistent with data.
- Spin-dependent charge exchange terms not well constrained by N-N scattering and possibly overestimated.

Note: Data are acceptance corrected; inner uncertainties are statistical only; full analysis of E03-104 will have reduced systematic uncertainties.
Bound Nucleon Wave Function

Pointlike Configurations (PLC)

- Smaller average interaction strength
- PLC suppressed in the bound state
- Contribution of PLCs exhibit a strong momentum dependence (arising from the reduction of the interaction strength)

Ciofi degli Atti et al. argue that medium modifications should strongly depend on the nucleon momentum (nucleon virtuality)

\[ v = p^2 - m_N^2 \]
\[ = (M_A - \sqrt{(M_A - m_N + E)^2 + p^2})^2 - p^2 - m_N^2 \]

- At \( v = 0 \), modification should vanish.
- “Would be nice to study modification of the nucleon form factors as a function of the nucleon momentum.” [Mark Strikman]

C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C 76, 055206 (2007)
M.R. Frank, B.K. Jennings, G.A. Miller, Phys. Rev. C 54, 920 (1996)
Proton Virtuality – Suppression of PLCs?

- Polarization-transfer double ratio shows (linear) dependence on proton virtuality with the trend of $R \approx 1$ for $p^2 = m^2_N$
- Excellent description with the RDWIA + QMC model.
Summary

• Models predict change of the internal structure of bound nucleon

• Recoil-polarization in $^4\text{He}(e,e'p)^3\text{H}$
  
  ▶ Two polarization observables act together to constrain the interpretation of the data
    
    • Polarization transfer: sensitive to in-medium form factors
    
    • Induced polarization: sensitive to final-state interactions, not sensitive to in-medium form factors

• Preliminary results
  
  ▶ Data effectively described by in-medium electromagnetic form factors or strong charge-exchange FSI
  
  ▶ Induced polarization crucial to clarify role of FSI and new results from E03-104 will provide needed constraints