Hadrons in the Nuclear Medium

Unpolarized Quasielastic Electron Scattering

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26th Annual Hampton University Graduate Studies Program
Jefferson Lab, Newport News, Virginia
May 31 – June 17, 2011
Electron Scattering from a Nuclear Target

\[ q = k_e - k_{e'} \equiv (\omega, \mathbf{q}) \]

\[
\frac{d^2 \sigma}{d\Omega_e \, dE_{e'}} = \left( \frac{d\sigma}{d\Omega_{e'}} \right)_M \left[ W_2(|\mathbf{q}|, \omega) + 2W_1(|\mathbf{q}|, \omega) \tan^2 \frac{\theta}{2} \right]
\]

y-Scaling

• The inclusive cross section is a function of two independent variables, \( q \) and \( \omega \). Scaling refers to the dependence of the cross section on a single variable \( y(\omega, q) \).

• Energy and momentum conservation (IA)

\[
\omega + m - E = \sqrt{(\vec{k} + \vec{q})^2 + m^2 + E_{\text{recoil}}}
\]

• For sufficiently large \( q \) (neglecting \( E, E_{\text{recoil}}, k_\perp^2 \))

\[
(\omega + m)^2 = k_\parallel^2 + 2k_\parallel |\vec{q}| + |\vec{q}|^2 - m^2
\]

• \( k_\parallel = y(\omega, q) \); \( q \) and \( \omega \) are no longer independent variables.

y-Scaling (II)

- Under certain approximations, the cross section can be written as:

\[
\frac{d^2\sigma}{d\Omega_e d\omega} \approx \bar{\sigma}_e(q,y) \cdot F(y)
\]

quantity related to the elementary electron nucleon cross section

\(F(y)\) = probability to find in the nucleus a nucleon of momentum component \(y\) parallel to \(q\)

- \(y\)-scaling in quasi-elastic electron-nucleus scattering reveals the nucleon momentum distribution in the nucleus.

y-Scaling (III)

- 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 sensitive to change of nucleon radius
- Limits: $Q^2 > 1 \text{ (GeV/c)}^2$ : $\Delta G_M < 3\%$

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

Quasielastic A(e,e') Scattering

Rosenbluth technique

\[
\frac{d\sigma}{d\Omega d\omega} \frac{\epsilon}{\sigma_M Q^4} = \Sigma
\]

\[
\Sigma = \epsilon R_L(q,\omega) + \frac{q^2}{2Q^2} R_T(q,\omega)
\]

- Requires measurement at fixed q and varying \( \epsilon \)
- Rosenbluth technique is only applicable in PW born approximation
- Important corrections due to Coulomb distortions of the electron waves

Coulomb Sum Rule

- **L/T Separation**
  - Transverse response: contributions from meson exchange currents and $\Delta$ excitation
  - Longitudinal response: Coulomb Sum Rule

- **Coulomb Sum Rule**
  - Non-relativistic regime
  - Short-range correlations between nucleons and the effect of Pauli blocking is neglected

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

- Experimental findings controversial
  - No quenching in the data observed [1]
  - Quenching of $S_L$ is experimentally established [2]
- Good agreement between theory and experiment for $^4$He when using free-nucleon form factors [3]
- Limits: $Q^2 \leq 0.5$ (GeV/c)$^2$: $\Delta G_E < 15\%$ or even $< 5\%$
- New data expected from JLab E05–110 [Choi, Chen, and Meziani]

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$S_L$ in $^{56}$Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jourdan</td>
<td>$0.91 \pm 0.12$</td>
</tr>
<tr>
<td>Morgenstern, Meziani</td>
<td>$0.73 \pm 0.12$</td>
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</tbody>
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Some Modern Models of In-Medium Nucleons

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Quark-Meson Coupling Model (QMC)

- Lagrangian density for the QMC model (symmetric nuclear matter)

\[ L_q = \bar{q}(i\gamma^\mu\delta_\mu - m_q)q\theta_v - B_0\theta_v + g_\sigma^q\bar{q}q\sigma - g_\omega^q\bar{q}\gamma_\mu q\omega^\mu - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega^2 \]

- Solve equations self-consistently:
  - The meson fields are given by the nucleon densities in the nucleus
  - The nucleon structure is determined by the quarks coupling to the mesons

- Modification of internal structure of bound nucleons

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

At low $Q^2$: Charge form factor much more sensitive to the nuclear medium than the magnetic one.

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

Chiral Solitons in Nuclei

- Three constituent quarks interact with pions.
- The central mechanism to explain the EMC effect is that the nuclear medium provides an attractive scalar interaction that modifies the nucleon wave function.
- Quark scalar and pseudoscalar densities

\[
\rho_s^q(r) = \langle \bar{\psi} \psi \rangle_0 + \rho_s^v(r) + \tilde{c}_s \int d^3r' \rho_s^N(r') \rho_s^v(r-r') \\
\rho_{ps}^q(r) \approx \rho_{ps}^v(r)
\]

- Chiral-soliton model provides the quark and antiquark substructure of the proton, embedded in nuclear matter.
- Two free parameters: \( \langle \psi \psi \rangle_0 \) and \( g_v \); effective condensate falls 30% at nuclear density.

Chiral Solitons in Nuclei

- The CQS model consistent with free nucleon properties, nuclear saturation properties, EMC effect, Drell-Yan experiments

- Medium induced increase of nucleon radius = 2.4%; consistent with A(e,e'p) limit of < 6%.

Chiral Quark Soliton Model (CQS)

- Density-dependent medium modifications:
  - significant for $G_E$, only moderate for $G_M$
  - no strong enhancement of the magnetic moment

- sea quarks almost completely unaffected (magnetic form factor)

In-Medium Form Factors

- Changes in the internal structure of bound nucleons result also in bound nucleon form factors.

- Observable effects predicted:
  - Chiral Quark Soliton (CQS),
  - Quark Meson Coupling (QMC),

- Model Predictions:
  - are density and $Q^2$ dependent,
  - show similar behavior,
  - consistent with experimental data (within large uncertainties).

NJL: I.C. Cloet, W. Bentz, and A.W. Thomas (to be published)