Role of Correlations and Two-Body Currents in Quasielastic (QE) $e/\nu$ Scattering

R. Schiavilla

Theory Center, Jefferson Lab, Newport News, VA 23606, USA
Physics Department, Old Dominion University, Norfolk, VA 23529, USA

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Role correlations and two-body currents in QE $e/\nu$ scattering

Outline:

- Nuclear interactions
- Correlations and short-range structure
- Nuclear electroweak currents
- Inclusive $e/\nu$ scattering and two-body currents
- Role of interference between 1b and 2b currents
- Summary

In collaboration with:

A. Lovato  S. Gandolfi  L.E. Marcucci  S. Pastore
J. Carlson  S.C. Pieper  G. Shen  R.B. Wiringa
Nuclear interactions

- $v = v_0(\text{static}) + v_p(\text{momentum dependent}) \rightarrow v(\text{OPE})$
  - fits large $NN$ database with $\chi^2 \simeq 1$

$NN$ interactions alone fail to predict:
- spectra of light nuclei
- Intermediate-energy $Nd$ and low-energy $n-\alpha$ scattering
- nuclear matter $E_0(\rho)$

Inclusion of $2\pi$ and $3\pi$-$NNN$ interactions leads to an excellent description of spectra of $s$- and $p$-shell nuclei
  (and $n-\alpha$ scattering)
Nuclear interactions

\[ v = v_0 \text{(static)} + v_p \text{(momentum dependent)} \rightarrow v \text{(OPE)} \]
fits large \( NN \) database with \( \chi^2 \approx 1 \)

- \( NN \) interactions alone fail to predict:
  - spectra of light nuclei
  - Intermediate-energy \( Nd \) and low-energy \( n-\alpha \) scattering
  - nuclear matter \( E_0(\rho) \)

- Inclusion of \( 2\pi \) and \( 3\pi \)-\( NNN \) interactions leads to an excellent description of spectra of \( s \)- and \( p \)-shell nuclei (and \( n-\alpha \) scattering)
Spectra of light nuclei

Pieper and Wiringa, private communication

-40
-50
-60
-70
-80
-90
-100
0+
1+
2+
3+
4+
5/2+
1/2+
3/2+
5/2−
7/2−
2+
3+
4+
5/2+
7/2+
0+
1+
2+
3+
4+

4He 6He 6Li 7Li 8Li 8Be 9Li 9Be 10Be 10B 12C

Argonne v18
With Illinois-7
GFMC Calculations

AV18 +IL7
Expt.
Dominant features of two-nucleon potential

- Short-range repulsion (common to many systems)
- Intermediate to long-range tensor character (unique to nuclei)
- Strong spin and isospin-dependent correlations

\[ \nu \text{ in } T,S=0,1 \text{ (d-like)} \]

\[ \nu \text{ in } T,S=1,0 \text{ (quasi-bound)} \]
Impact on pair spatial distributions

Forest et al. (1996)

$\rho_{T=0,S=1}(r)$ depends on $r$ and $M_S$:

- Universality of short-range structure: scaling of $\rho_{T,S}(r)$
Impact on pair momentum distributions

Wiringa et al. (2014)
Impact on pair momentum distributions

Wiringa et al. (2014)
Set of (conserved) EM current operators

\[ j = j^{(1)} + j^{(2)}(\nu) + j^{(3)}(V^{2\pi}) \]

contain no free parameters and are consistent with short-range behavior of \( \nu \) and \( V^{2\pi} \)

Many-body EM charge operators represent relativistic corrections to \( \rho^{(1)} \), and lead to small corrections

These many-body corrections are important to reproduce a variety of nuclear EM observables
Leading two-body currents are isovector

Two-body charge contributions, while small, crucial for reproducing $^2$H, $^3$H, $^3$He, and $^4$He exp longitudinal f.f.'s
Weak current operators

- Charge-changing ($CC$) and neutral ($NC$) weak currents

$$j_{CC}^\mu = j_\pm^\mu + j_\mp^\mu$$

$$j_{NC}^\mu = -2 \sin^2 \theta_W j_{\gamma,S}^\mu + (1 - 2 \sin^2 \theta_W) j_{\gamma,z}^\mu + j_z^\mu$$

- Contributions to two-body axial currents from $\pi$ and $\rho$ exchange, $\rho \pi$ transition, and $\Delta$-excitation ($g_A^*$)

- $\mathcal{N}$-$\Delta$ axial coupling constant $g_A^*$ fixed by fitting the GT m.e. in $^3$H $\beta$-decay

- $j_{CC}^\mu$ reproduces well $\mu$-capture rates in $^2$H and $^3$He

- Studies of weak transitions in light nuclei in progress...
Inclusive \( e/\nu \) scattering

- Inclusive \( \nu/\bar{\nu} \) (\(-/+)\) cross section given in terms of five response functions

\[
\frac{d\sigma}{d\epsilon' d\Omega} = \frac{G^2}{8 \pi^2} \frac{k'}{\epsilon} \left[ v_{00} R_{00} + v_{zz} R_{zz} - v_{0z} R_{0z} + v_{xx} R_{xx} + v_{xy} R_{xy} \right]
\]

\[
R_{\alpha\beta}(q, \omega) \sim \sum_i \sum_f \delta(\omega + m_A - E_f) \langle f | j^\alpha(q, \omega) | i \rangle^* \langle f | j^\beta(q, \omega) | i \rangle
\]

- In \((e, e')\) scattering, interference \(R_{xy} = 0\), \(j^\gamma \sim (\omega/q) j^0\gamma\), and only \(R_{00} = R_L\) and \(R_{xx} = R_T\) are left
Scaling variables: $\psi' \simeq y/k_F$ and $f_{L,T} = k_F R_{L,T}/G_{L,T}$

Data at variance with PWIA expectation that $f_L \simeq f_T$

Excess strength in transverse response

Notion that the QE response is dominated by single-nucleon scattering is too simplistic
Sum rules for \((e, e')\) inclusive scattering

Schiavilla et al. (1989); Carlson et al. (2002)

\[ S_\alpha(q) = C_\alpha \int_{\omega_{th}^+}^{\infty} d\omega \frac{R_\alpha(q, \omega)}{G_{Ep}^2(q, \omega)} \]

\[ = C_\alpha \left[ \langle 0 | O^\dagger_\alpha(q) O_\alpha(q) | 0 \rangle - |\langle 0 | O_\alpha(q) | 0 \rangle|^2 \right] \]

- \(C_\alpha\) are normalization factors so as \(S_\alpha(q \to \infty) = 1\) when only one-body terms are retained in \(O_\alpha\):

\[ C_L = \frac{1}{Z} , \quad C_T = \frac{2m^2}{q^2} \frac{1}{Z \mu_p^2 + N \mu_n^2} \]

- \(S_\alpha\) can be calculated exactly with quantum Monte Carlo methods
Direct comparison between theory and experiment problematic, especially for $R_T(q, \omega)$:

- $R_\alpha(q, \omega)$ measured by $(e, e')$ up to $\omega_{\text{max}} \leq q$
- Present theory ignores explicit pion production mechanisms, crucial in the $\Delta$-peak region of $R_T$

Contribution for $\omega > \omega_{\text{max}}$ estimated by assuming

$$R_\alpha^{\text{EXP}}(q, \omega > \omega_{\text{max}}; A) \propto R_\alpha(q, \omega; \text{deuteron})$$
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\[
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\]
EM euclidean response functions in \(^4\)He

Carlson and Schiavilla (1992, 1994); Carlson et al. (2002)

\[
E_\alpha(q, \tau) = e^{\tau q^2/(2m)} \int_{\omega_{\text{th}}^+}^{\infty} d\omega \ e^{-\tau(\omega-E_0)} \frac{R_\alpha(q, \omega)}{G^2_{Ep}(q, \omega)}
\]

\[
= e^{\tau q^2/(2m)} \langle 0 | O_\alpha^\dagger(q) e^{-\tau(H-E_0)} O_\alpha(q) | 0 \rangle - (\text{elastic})
\]

- At \(\tau = 0\), \(E_\alpha(q; 0) \propto S_\alpha(q)\); as \(\tau\) increases, \(E_\alpha(q; \tau)\) probes strength in QE region
Weak NC $S_{xx}(q)$ (transverse) sum rule in $^{12}$C

Lovato et al. (2014)

$$S_{xx}(q) = C_{xx} \int_{\omega_{el}}^{\infty} d\omega R_{xx}(q, \omega) = C_{xx} \langle 0 | j_{NC}^\perp(q) j_{NC}^\perp(q) | 0 \rangle$$

- Large increase ($\sim 30\%$) in all weak NC responses $R_\alpha$, but for $R_{00}$, due to two-body (2b) terms in $j_{NC}^\mu$
- Important interference effects between 1b and 2b (as well as among 2b) terms
1b-2b interference effects: sum rules

\[ S - S^{1b} = \langle A | \left( j_{1b}^{\dagger} j_{2b} + \text{h.c.} \right) + j_{2b}^{\dagger} j_{2b} | A \rangle \]

\[ \Delta S \simeq \langle A | \sum_{l<m} \left[ (j_l^{\dagger} + j_m^{\dagger}) j_{lm} + \text{h.c.} \right] + \sum_{l<m} j_{lm}^{\dagger} j_{lm} + \cdots | A \rangle \]

\[ = \int dx \ j(x) \rho^A(x; pn) \]

- Enhancement \( \Delta S \) driven by \( pn \) pairs
- Scaling law for \( \Delta S \) follows from scaling of \( \rho^A(x; pn) \)
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- Enhancement \( \Delta S \) driven by \( pn \) pairs
- Scaling law for \( \Delta S \) follows from scaling of \( \rho^A(x; pn) \)
Baseline: the Fermi gas response

Van Orden and Donnelly (1981)

Excited states of the Fermi gas (up to $2p\hbar$ states):

$$|p\hbar\rangle = a_p^\dagger a_{\hbar} |0\rangle \text{ with } p > k_F; \ h < k_F$$

$$|p_1 p_2 h_1 h_2\rangle = a_{p_1}^\dagger a_{p_2}^\dagger a_{h_2} a_{h_1} |0\rangle \text{ with } p_1, p_2 > k_F; \ h_1, h_2 < k_F$$

One-body operator $j_{1b} = \sum_{kk'} j_{k,k'}^b a_{k'}^\dagger a_k$ and

$$\langle p\hbar | j_{1b} | 0\rangle = j_{\hbar}^p; \quad \langle p_1 p_2 h_1 h_2 | j_{1b} | 0\rangle = 0$$

Two-body operator $j_{2b} = \frac{1}{2} \sum_{k_1k_2k'_1k'_2} j_{k_1,k_2}^{k'_1,k'_2} a_{k_1'}^\dagger a_{k_2'}^\dagger a_{k_2} a_{k_1}$ and

$$\langle p\hbar | j_{2b} | 0\rangle = \sum_{k} \left( j_{h,h,k}^p - j_{h,k,k}^p \right) \theta(k_F - k); \quad \langle p_1 p_2 h_1 h_2 | j_{2b} | 0\rangle = j_{h_1,h_2,h_1}^{p_1,p_2} - j_{h_2,h_1,h_2}^{p_1,p_2}$$

Fermi gas response:

$$R(\omega) = \sum_{p\hbar} |\langle p\hbar | j_{1b} + j_{2b} | 0\rangle|^2 \delta(\omega + E_{1p\hbar})$$

$$+ \sum_{p_1 p_2 h_1 h_2} |\langle p_1 p_2 h_1 h_2 | j_{2b} | 0\rangle|^2 \delta(\omega + E_{2p\hbar})$$

$1p\hbar$ contribution involves interference between $1b$ and $2b$ currents
Baseline: the Fermi gas response

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- Excited states of the Fermi gas (up to \(2ph\) states):

\[
|ph\rangle = a\dagger_p a_h |0\rangle \quad \text{with } p > k_F; \; h < k_F
\]

\[
|p_1p_2h_1h_2\rangle = a\dagger_{p_1} a\dagger_{p_2} a_{h_2} a_{h_1} |0\rangle \quad \text{with } p_1, p_2 > k_F; \; h_1, h_2 < k_F
\]

- One-body operator \(j_{1b} = \sum_{kk'} j_{k,k'}^{\dagger} a_{k'}^\dagger a_k\) and

\[
\langle ph | j_{1b} | 0 \rangle = j_{h}^P; \quad \langle p_1p_2h_1h_2 | j_{1b} | 0 \rangle = 0
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\langle ph | j_{2b} | 0 \rangle = \sum_k \left( j_{h,k}^P - j_{k,h}^P \right) \theta(k_F - k); \quad \langle p_1p_2h_1h_2 | j_{2b} | 0 \rangle = j_{h_1,h_2}^{P_1,P_2} - j_{h_2,h_1}^{P_1,P_2}
\]

- Fermi gas response:

\[
R(\omega) = \sum_{ph} | \langle ph | j_{1b} + j_{2b} | 0 \rangle |^2 \delta(\omega + E_{1ph})
\]

\[
+ \sum_{p_1p_2h_1h_2} | \langle p_1p_2h_1h_2 | j_{2b} | 0 \rangle |^2 \delta(\omega + E_{2ph})
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One-body operator $j_{1b} = \sum_{kk'} j_{k}^{k'} a_{{k'}}^{{\dagger}} a_{{k}}$ and

$$\langle ph | j_{1b} | 0⟩ = j_{h}^{{p}} ; \quad \langle p_1p_2h_1h_2 | j_{1b} | 0⟩ = 0$$

Two-body operator $j_{2b} = \frac{1}{2} \sum_{k_1k_2k_1'k_2'} j_{k_1}^{k_1'} j_{k_2}^{k_2'} a_{{k_1'}}^{{\dagger}} a_{{k_2'}}^{{\dagger}} a_{{k_2}} a_{{k_1}}$ and

$$\langle ph | j_{2b} | 0⟩ = \sum_{k} \left( j_{h,k}^{{p,k}} - j_{k,h}^{{p,k}} \right) \theta(k_F - k) ; \quad \langle p_1p_2h_1h_2 | j_{2b} | 0⟩ = j_{h_1,h_2}^{{p_1,p_2}} - j_{h_2,h_1}^{{p_1,p_2}}$$

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$$+ \sum_{p_1p_2h_1h_2} |\langle p_1p_2h_1h_2 | j_{2b} | 0⟩|^2 \delta(\omega + E_{2ph})$$

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One-body operator $j_{1b} = \sum_{kk'} j^{k'}_k a_{k'}^\dagger a_k$ and

$$\langle ph | j_{1b} | 0 \rangle = j_P^h; \quad \langle p_1p_2h_1h_2 | j_{1b} | 0 \rangle = 0$$

Two-body operator $j_{2b} = 1/2 \sum_{k,k'} j^{k'}_k j^{k'}_k a_{k'}^\dagger a_k a_{k'}^\dagger a_k$ and

$$\langle ph | j_{2b} | 0 \rangle = \sum_k \left( j_{h,k}^p - j_{k,h}^p \right) \theta(k_F - k); \quad \langle p_1p_2h_1h_2 | j_{2b} | 0 \rangle = j_{h_1,h_2}^{p_1,p_2} - j_{h_2,h_1}^{p_1,p_2}$$

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\]

One-body operator \( j_{1b} = \sum_{kk'} j_{k}^{k'} a_{k'}^\dagger a_k \) and

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Two-body operator \( j_{2b} = \frac{1}{2} \sum_{k_1k_2k_1'k_2'} j_{k_1,k_2}^{k_1',k_2'} a_{k_1'}^\dagger a_{k_2'}^\dagger a_{k_2} a_{k_1} \) and

\[
\langle ph | j_{2b} | 0 \rangle = \sum_k \left( j_{h,k}^{p,k} - j_{k,h}^{p,k} \right) \theta(k_F - k); \quad \langle p_1p_2h_1h_2 | j_{2b} | 0 \rangle = j_{h_1,h_2}^{p_1,p_2} - j_{h_2,h_1}^{p_1,p_2}
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Fermi gas response:

\[
R(\omega) = \sum_{ph} |\langle ph | j_{1b} + j_{2b} | 0 \rangle|^2 \delta(\omega + E_{1ph}) \\
+ \sum_{p_1p_2h_1h_2} |\langle p_1p_2h_1h_2 | j_{2b} | 0 \rangle|^2 \delta(\omega + E_{2ph})
\]

1\( ph \) contribution involves interference between 1b and 2b currents
Baseline: the Fermi gas response
Van Orden and Donnelly (1981)

- Excited states of the Fermi gas (up to \(2p_h\) states):
  \[
  |p_h\rangle = a_p^\dagger a_h |0\rangle \text{ with } p > k_F; \ h < k_F
  \]
  \[
  |p_1p_2h_1h_2\rangle = a_{p_1}^\dagger a_{p_2}^\dagger a_{h_2}a_{h_1} |0\rangle \text{ with } p_1, p_2 > k_F; \ h_1, h_2 < k_F
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  \]

- Fermi gas response:
  \[
  R(\omega) = \sum_{p_h} |\langle p_h | j_{1b} + j_{2b} | 0 \rangle|^2 \delta(\omega + E_{1p_h})
  \]
  \[
  + \sum_{p_1p_2h_1h_2} |\langle p_1p_2h_1h_2 | j_{2b} | 0 \rangle|^2 \delta(\omega + E_{2p_h})
  \]

- \(1p_h\) contribution involves interference between \(1b\) and \(2b\) currents
Summary

- Enhancement of 1b response due to 2b currents driven by strongly correlated $pn$ pairs

- Presence of these correlated pairs leads to important interference effects between 1b and 2b currents:
  - 1b currents can knock-out two nucleons from a correlated ground state (with amplitude $A_{1b}$)
  - This same final state can be reached by acting with 2b currents on the correlated ground state (amplitude $A_{2b}$)
  - Response $\propto \sum_f |A_{1b}(f) + A_{2b}(f)|^2$

- These interference effects are fully accounted for in QMC calculations of response functions and sum rules
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