Electroweak Processes in the Few Nucleons: the Old and the New

- EM currents in the conventional approach
- EM currents in $\chi$EFT up to one loop
- A (sensitive) test case: radiative captures in $A=3$ and 4 systems
- Nuclear theory at 1%: $\mu$-capture in $d$ and $^3$H
- Summary and outlook

In collaboration with:
L. Girlanda    L. Marcucci    S. Pastore    M. Viviani
A. Kievsky    M. Piarulli    R.B. Wiringa

References:
Pastore et al. PRC\textbf{80}, 034004 (2009); Girlanda et al. PRL\textbf{105}, 232502 (2010);
Marcucci et al., PRC\textbf{83}, 014002 (2011)
Conventional approach: EM currents

Marcucci et al., PRC72, 014001 (2005)

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

- Static part \( v_0 \) of \( v \) from \( \pi \)-like (\( PS \)) and \( \rho \)-like (\( V \)) exchanges
- Currents from corresponding \( PS \) and \( V \) exchanges, for example

\[
j_{ij}(v_0; PS) = i \left( \tau_i \times \tau_j \right)_z \left[ v_{PS}(k_j) \sigma_i (\sigma_j \cdot k_j) \right] + \frac{k_i - k_j}{k_i^2 - k_j^2} v_{PS}(k_i) (\sigma_i \cdot k_i) (\sigma_j \cdot k_j) \] + i \rightleftharpoons j
\]

with \( v_{PS}(k) = v^{\sigma \tau}(k) - 2 v^{t \tau}(k) \) projected out from \( v_0 \) components

\[
j^{(2)}(v) \xrightarrow{\text{long range}} \quad \pi + \pi + \pi \pi \]

\( j \) transverse
• Currents from $v_p$ via minimal substitution in i) explicit and ii) implicit $p$-dependence, the latter from

$$\tau_i \cdot \tau_j = -1 + (1 + \sigma_i \cdot \sigma_j) \, e^{i(r_{ji} \cdot p_i + r_{ij} \cdot p_j)}$$

• Currents are conserved, contain no free parameters, and are consistent with short-range behavior of $v$ and $V^{2\pi}$, but are not unique

Variety of EM observables in $A=2–7$ nuclei well reproduced, including $\mu$’s and $M1$ widths, elastic and inelastic f.f.’s, inclusive response functions, . . .

Current predictions for $^2H(n, \gamma)^3H$ and $^3He(n, \gamma)^4He$ cross-sections shown later
$^{2}\text{H}(p, \gamma)^{3}\text{He}$ capture at low energies

![Graph showing the cross-section $^{3}\text{He}(p, \gamma)^{4}\text{He}$ for different energies.](image-url)
**Nuclear $\chi$EFT approach**

Weinberg, PLB**251**, 288 (1990); NPB**363**, 3 (1991); PLB**295**, 114 (1992)

- $\chi$EFT exploits the $\chi$-symmetry exhibited by QCD to restrict the form of $\pi$ interactions with other $\pi$’s, and with $N$’s, $\Delta$’s, . . .
- The pion couples by powers of its momentum $Q$, and $\mathcal{L}_{\text{eff}}$ can be systematically expanded in powers of $Q/\Lambda_\chi$ ($\Lambda_\chi \simeq 1$ GeV)

$$
\mathcal{L}_{\text{eff}} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + ... 
$$

- $\chi$EFT allows for a perturbative treatment in terms of a $Q$–as opposed to a coupling constant–expansion
- The unknown coefficients in this expansion–the LEC’s–are fixed by comparison with experimental data
- Nuclear $\chi$EFT provides a practical calculational scheme, susceptible (in principle) of systematic improvement
Work in nuclear $\chi$EFT: a partial listing

Since Weinberg’s papers (1990–92), nuclear $\chi$EFT has developed into an intense field of research. A very incomplete list:

- $NN$ and $NNN$ potentials:
  - van Kolck et al. (1994–96)
  - Kaiser, Weise et al. (1997–98)
  - Glöckle, Epelbaum, Meissner et al. (1998–2005)
  - Entem and Machleidt (2002–03)

- Currents and nuclear electroweak properties:
  - Rho, Park et al. (1996–2009), hybrid studies in $A=2–4$
  - Meissner et al. (2001), Kölling et al. (2009–2010)
  - Phillips (2003), deuteron static properties and f.f.’s

Lots of work in pionless EFT too …
Formalism

- Time-ordered perturbation theory (TOPT):

\[ -\frac{\hat{e}_q \lambda}{\sqrt{2} \omega_q} \cdot j = \langle N'N' | T | N N; \gamma \rangle \]

\[ = \langle N'N' | H_1 \sum_{n=1}^{\infty} \left( \frac{1}{E_i - H_0 + i \eta} H_1 \right)^{n-1} | N N; \gamma \rangle \]

- Power counting:

\[ T = T^{LO} + T^{NLO} + T^{N^2LO} + \ldots, \text{ and } T^{N^nLO} \sim (Q/\Lambda) \times T^{LO} \]

- Irreducible and recoil-corrected reducible contributions retained in \( T \) expansion

- A contribution with \( N \) interaction vertices and \( L \) loops scales as

\[ e \left( \prod_{i=1}^{N} Q^{\alpha_i - \beta_i/2} \right) \times Q^{-(N-1)} \times Q^{3L} \]

\[ \alpha_i = \text{number of derivatives (momenta)} \quad \beta_i = \text{number of } \pi \text{'s at each vertex} \]
Two-body EM currents in $\chi$EFT up to $N^2$LO ($eQ^0$)

- **LO**: $eQ^{-2}$
- **NLO**: $eQ^{-1}$
- **$N^2$LO**: $eQ^0$

- These depend on the proton and neutron $\mu$'s ($\mu_p = 2.793 \mu_N$ and $\mu_n = -1.913 \mu_N$), $g_A$, and $F_\pi$.
- One-loop corrections to one-body current are absorbed into $\mu_N$ and $\langle r_N^2 \rangle$. 
N$^3$LO ($e Q$) corrections

- One-loop corrections:

- Tree-level current with one $e Q^2$ vertex from $\mathcal{L}_{\gamma \pi N}$ of Fettes et al. (1998), involving 3 LEC’s ($\sim \gamma N \Delta$ and $\gamma \rho \pi$ currents):

- Contact currents

from i) minimal substitution in the interactions involving $\partial N$ (7 LEC’s determined from strong-interaction sector) and ii) non-minimal couplings (2 LEC’s)
Technical issues I: recoil corrections at $N^2$LO

- $N^2$LO reducible and irreducible contributions in TOPT

$$j^{N^2LO} = \begin{array}{c}
\text{Reducible} \\
\text{Irreducible}
\end{array}$$

- Recoil corrections to the reducible contributions obtained by expanding in powers of $(E_i - E_I)/\omega_{\pi}$ the energy denominators

$$\begin{align*}
\frac{E_i - E_I}{\omega_{\pi}} &= \nu_{\pi} \left( 1 + \frac{E_i - E_I}{2\omega_{\pi}} \right) \frac{1}{E_i - E_I} j^{LO} \\
\frac{E_i - E_I}{2\omega_{\pi}} &= -\frac{\nu_{\pi}}{2\omega_{\pi}} j^{LO}
\end{align*}$$

- Recoil corrections to reducible diagrams cancel irreducible contribution
Technical issues II: recoil corrections at N³LO

\[ j^{N^3LO} = \begin{array}{c}
\text{Direct} \\
\text{Crossed}
\end{array} \]

- Reducible contributions

\[ j_{\text{red}} = \int \frac{1}{E_i - E_I} J^{NLO}(q_1) \]
\[ -2 \int \frac{\omega_1 + \omega_2}{\omega_1 \omega_2} V_{\pi NN}(2, q_2) V_{\pi NN}(2, q_1) V_{\pi NN}(1, q_2) V_{\gamma \pi NN}(1, q_1) \]

- Irreducible contributions

\[ j_{\text{irr}} = 2 \int \frac{\omega_1 + \omega_2}{\omega_1 \omega_2} V_{\pi NN}(2, q_2) V_{\pi NN}(2, q_1) V_{\pi NN}(1, q_2) V_{\gamma \pi NN}(1, q_1) \]
\[ + 2 \int \frac{\omega_1^2 + \omega_2^2 + \omega_1 \omega_2}{\omega_1 \omega_2 (\omega_1 + \omega_2)} [V_{\pi NN}(2, q_1), V_{\pi NN}(2, q_2)] - V_{\pi NN}(1, q_2) V_{\gamma \pi NN}(1, q_1) \]

- Partial cancellations between recoil corrections to reducible diagrams and irreducible contributions
Nuclear $\chi$EFT (at $Q^2$ and $eQ$)

$NN$ potential:

and accompanying set of conserved EM currents:

- **LO**: $eQ^{-2}$
- **NLO**: $eQ^{-1}$
- **N^2LO**: $eQ^0$
- **N^3LO**: $eQ$
Fits to \( np \) phases up to \( T_{\text{LAB}} = 100 \text{ MeV} \)

\[ \text{LS-equation regulator} \sim \exp\left(-\frac{Q^4}{\Lambda^4}\right) \] with \( \Lambda = 500, 600, \text{ and } 700 \text{ MeV} \) (cutting off momenta \( Q \gtrsim 3-4 \, m_\pi \))
Deuteron properties

<table>
<thead>
<tr>
<th></th>
<th>Λ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td>$B_d$ (MeV)</td>
<td>2.2244</td>
</tr>
<tr>
<td>$\eta_d$</td>
<td>0.0267</td>
</tr>
<tr>
<td>$r_d$ (fm)</td>
<td>1.943</td>
</tr>
<tr>
<td>$\mu_d$ ($\mu_N$)</td>
<td>0.860</td>
</tr>
<tr>
<td>$Q_d$ (fm$^2$)</td>
<td>0.275</td>
</tr>
<tr>
<td>$P_D$ (%)</td>
<td>3.44</td>
</tr>
</tbody>
</table>
Previous (and contemporary) work on $\chi$EFT currents

- Expressions for two-body currents (and potential, of course) at one loop in agreement with those of Kölling et al. (2009) derived via TOPT and the unitary transformation method.
- Park et al. (1996) use covariant perturbation theory, but obtain different isospin structure for these loop currents: differences in treatment of box diagrams.
EM observables at N$^3$LO

- Pion loop corrections and (minimal) contact terms known
- Five LEC’s: $d^S$, $d^V_1$, and $d^V_2$ could be determined by pion photo-production data on the nucleon

$$d^S, d^V_1, d^V_2 \quad c^S, c^V$$

- $d^V_2/d^V_1 = 1/4$ assuming $\Delta$-resonance saturation
- Three-body currents at N$^3$LO vanish:
Fixing LEC’s in EM Properties of A=2 and A=3 Nuclei

AV18/UIX or N^3 LO/TNI-N^2 LO (band)

- \( \mu_d \)
- \( \mu_S (^3\text{He}/^3\text{H}) \)
- \( \mu_V (^3\text{He}/^3\text{H}) \)
- np capture

\( \Lambda \) (MeV)
Fitted LEC values

- LEC’s—in units of $\Lambda$—corresponding to $\Lambda = 500–700$ MeV for AV18/UIX (N3LO/N2LO)
- Isoscalar $d^S (c^S)$ and isovector $d^V_1 (c^V)$ associated with higher-order $\gamma\pi N$ (contact) currents

\[
\begin{array}{ccccc}
\Lambda & \Lambda^2 d^S \times 10^2 & \Lambda^4 c^S & \Lambda^2 d^V_1 & \Lambda^4 c^V \\
500 & -8.85 (-0.225) & -3.18 (-2.38) & 5.18 (5.82) & -11.3 (-11.4) \\
600 & -2.90 (9.20) & -7.10 (-5.30) & 6.55 (6.85) & -12.9 (-23.3) \\
700 & 6.64 (20.4) & -13.2 (-9.83) & 8.24 (8.27) & -1.70 (-46.2) \\
\end{array}
\]
The nd and n$^3$He radiative captures

- Suppressed M1 processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\text{exp}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}(n,\gamma)^2\text{H}$</td>
<td>334.2(5)</td>
</tr>
<tr>
<td>$^2\text{H}(n,\gamma)^3\text{H}$</td>
<td>0.508(15)</td>
</tr>
<tr>
<td>$^3\text{He}(n,\gamma)^4\text{He}$</td>
<td>0.055(3)</td>
</tr>
</tbody>
</table>

- The $^3\text{H}$ and $^4\text{He}$ bound states are approximate eigenstates of the one-body M1 operator, e.g. $\hat{\mu}(\text{IA}) |^3\text{H}\rangle \simeq \mu_p |^3\text{H}\rangle$ and $\langle nd | \hat{\mu}(\text{IA}) |^3\text{H}\rangle \simeq 0$ by orthogonality.

- $A=3$ and 4 radiative (and weak) captures very sensitive to i) small components in the w.f.’s and ii) many-body terms in the electro(weak) currents (80-90% of cross section!)
Wave functions: recent progress

- 3 and 4 bound-state w.f.’s and 2+1 continuum routine by now
- Challenges with 3+1 continuum:
  1. Coupled-channel nature of scattering problem: $n^{-3}$He and $p^{-3}$H channels both open
  2. Peculiarities of $^4$He spectrum (see below): hard to obtain numerically converged solutions

- Major effort by several groups*: both singlet and triplet $n^{-3}$He scattering lengths in good agreement with data

* Deltuva and Fonseca (2007); Lazauskas (2009); Viviani et al. (2010)
### Triplet scattering length $a_1$ (fm)

<table>
<thead>
<tr>
<th>Method</th>
<th>AV18</th>
<th>AV18/UIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH</td>
<td>$3.56 - i 0.0077$</td>
<td>$3.39 - i 0.0059$</td>
</tr>
<tr>
<td>RGM</td>
<td>$3.45 - i 0.0066$</td>
<td>$3.31 - i 0.0051$</td>
</tr>
<tr>
<td>FY</td>
<td>$3.43 - i 0.0082$</td>
<td>$3.23 - i 0.0054$</td>
</tr>
<tr>
<td>AGS</td>
<td>$3.51 - i 0.0074$</td>
<td></td>
</tr>
<tr>
<td>R-matrix</td>
<td>$3.29 - i 0.0012$</td>
<td></td>
</tr>
<tr>
<td>EXP</td>
<td>$3.28(5) - i 0.001(2)$</td>
<td></td>
</tr>
<tr>
<td>EXP</td>
<td>$3.36(1)$</td>
<td></td>
</tr>
<tr>
<td>EXP</td>
<td>$3.48(2)$</td>
<td></td>
</tr>
</tbody>
</table>

Singlet scattering length $a_0$ (harder to calculate!) also in good agreement with experiment.
The table shows the radiative capture cross sections in $\mu$b for the reactions $n-d$ and $n-^3$He. The cross sections are given at different energies $\Lambda$ and include approximations from LO to N3LO.

### $n-d$ radiative capture cross section* in $\mu$b: $\sigma^{\text{EXP}}_{\text{nd}} = 508(15) \ \mu$b

<table>
<thead>
<tr>
<th>$\Lambda$</th>
<th>LO</th>
<th>NLO</th>
<th>N$^2$LO</th>
<th>N$^3$LO(L)</th>
<th>N$^3$LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>231</td>
<td>343</td>
<td>322</td>
<td>272</td>
<td>487</td>
</tr>
<tr>
<td>600</td>
<td>231</td>
<td>369</td>
<td>348</td>
<td>306</td>
<td>491</td>
</tr>
<tr>
<td>700</td>
<td>231</td>
<td>385</td>
<td>362</td>
<td>343</td>
<td>493</td>
</tr>
</tbody>
</table>

### $n-^3$He radiative capture cross section* in $\mu$b: $\sigma^{\text{EXP}}_{n^3\text{He}} = 55(4) \ \mu$b

<table>
<thead>
<tr>
<th>$\Lambda$</th>
<th>LO</th>
<th>NLO</th>
<th>N$^2$LO</th>
<th>N$^3$LO(L)</th>
<th>N$^3$LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>15.2</td>
<td>5.95</td>
<td>0.91</td>
<td>1.36</td>
<td>48.3</td>
</tr>
<tr>
<td>600</td>
<td>15.2</td>
<td>10.2</td>
<td>2.87</td>
<td>0.04</td>
<td>53.0</td>
</tr>
<tr>
<td>700</td>
<td>15.2</td>
<td>11.5</td>
<td>3.56</td>
<td>0.38</td>
<td>56.6</td>
</tr>
</tbody>
</table>

* N3LO/N2LO potentials and HH wave functions
\(\mu\)-Capture

From http://www.npl.illinois.edu/exp/musun/
Single-nucleon weak current

\[ \langle n | \bar{d} \gamma_\mu (1 - \gamma_5) u | p \rangle = \bar{u}_n \left( F_1 \gamma_\mu + \frac{i}{2m} F_2 \sigma_{\mu\nu} q^\nu - G_A \gamma_\mu \gamma_5 - \frac{1}{m_\mu} G_{PS} \gamma_5 q_\mu \right) u_p \]

- Additional scalar and pseudotensor f.f.’s, associated with second-class currents, possible (discussed later . . .)
- \( F_1(q^2) \) and \( F_2(q^2) \) related to EM f.f.’s via CVC: well known
- \( G_A(q^2) = g_A/(1 + q^2/\Lambda_A^2)^2 \): \( g_A \) known from neutron \( \beta \)-decay and \( \Lambda_A \simeq 1 \text{ GeV} \) from \( \pi \)-electroproduction and \( p(\nu_\mu, \mu^+)n \) data
- \( G_{PS}(q^2) \) poorly known: PCAC and \( \chi \)PT predict

\[ G_{PS}(q^2) = \frac{2m_\mu g_{\pi pn} F_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_A m_\mu m r_A^2 \]

\( G_{PS}(q_0^2) = 8.2 \pm 0.2 \) at \( q_0^2 = -0.88 m_\mu^2 \) relevant for \( p(\mu^-, \nu_\mu)n \)
Experimental situation I: $\mu^- + p$

Muon Capture Results

2005: $\Lambda_s = 725.0 \pm 13.7$ (stat) $\pm 10.7$ (syst) s$^{-1}$

$g_p (q^2 = -0.88 m_{\mu}^2) = 7.3 \pm 1.1$

Goal for 2006/2007 dataset is $\Lambda_s$ to $\pm 5$ s$^{-1}$

From Gorringe’s talk at Elba XI (2010).
Experimental situation II: $\mu^- + d$

Two hyperfine states: $1/2$ and $3/2 \Rightarrow \Gamma_D$ and $\Gamma_Q$
From theory: $\Gamma_D \simeq 400 \text{ s}^{-1}$ and $\Gamma_Q \simeq 10 \text{ s}^{-1} \Rightarrow$ only $\Gamma_D$

- Wang et al., PR 139, B1528 (1965): $\Gamma_D = 365(96) \text{ s}^{-1}$
- Bertini et al., PRD 8, 3774 (1973): $\Gamma_D = 445(60) \text{ s}^{-1}$
- Bardin et al., NPA 453, 591 (1986): $\Gamma_D = 470(29) \text{ s}^{-1}$
- Cargnelli et al., Workshop on fundamental $\mu$ physics, Los Alamos, 1986, LA10714C: $\Gamma_D = 409(40) \text{ s}^{-1}$
- MuSun Collaboration: result to come!
Experimental situation III: $\mu^- + ^3\text{He} \rightarrow ^3\text{H} + \nu_\mu$

Total capture rate $\Gamma_0$:

- Folomkin et al., PL 3, 229 (1963): $\Gamma_0 = 1410(140) \text{ s}^{-1}$
- Auerbach et al., PR 138, B127 (1967): $\Gamma_0 = 1505(46) \text{ s}^{-1}$
- Clay et al., PR 140, B587 (1965): $\Gamma_0 = 1465(67) \text{ s}^{-1}$
- Ackerbauer et al., PLB 417, 224 (1998): $\Gamma_0 = 1496(4) \text{ s}^{-1}$

Angular correlation $A_v$:

- Souder et al., NIMA 402, 311 (1998): $A_v = 0.63 \pm 0.09$ (stat.)$^{+0.11}_{-0.14}$ (syst.)
Nuclear weak currents

Two-body weak currents:

- Vector currents from isovector components of $j_\gamma$ (CVC)
- In SNPA the leading contribution in the axial currents is from $\Delta$-excitation, additional $\pi$- and $\rho$-meson contributions turn out to be tiny

- Axial currents in $\chi$EFT at N$^3$LO, derived in Park et al. (2003), depend on a single LEC $d_R$

Common strategy: fix $g^*_A$ in SNPA and $d_R(\Lambda)$ in $\chi$EFT by fitting the GT m.e. in $^3\text{H}$ $\beta$-decay
SNPA and χEFT predictions I: $\Gamma_0(\mu^- + ^2\text{H})$
SNPA and $\chi$EFT predictions II: $\Gamma_0(\mu^- + ^3\text{He})$

<table>
<thead>
<tr>
<th>SNPA (AV18/UIX)</th>
<th>$\Gamma_0$ s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_A=1.2654(42)$</td>
<td>1486(8)</td>
</tr>
<tr>
<td>$g_A=1.2695(29)$</td>
<td>1486(5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\chi$EFT*(AV18/UIX)</th>
<th>$\Gamma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda = 500$ MeV</td>
<td>1487(8)</td>
</tr>
<tr>
<td>$\Lambda = 600$ MeV</td>
<td>1488(9)</td>
</tr>
<tr>
<td>$\Lambda = 800$ MeV</td>
<td>1488(8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\chi$EFT (N3LO/N2LO; $\Lambda=600$ MeV)</th>
<th>$\Gamma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1480(9)</td>
</tr>
</tbody>
</table>

- Theory ($G_{PS}$ from $\chi$PT): $\Gamma_0 = 1484(13)$ s$^{-1}$

- With radiative corrections from Czarnecki, Marciano, and Sirlin (2007): $\Gamma_0 = 1494(13)$ s$^{-1}$ vs. $\Gamma_0(\text{exp}) = 1496(4)$ s$^{-1}$
\( \Gamma_0(\mu^- + ^3\text{He}) \) and second class currents

Standard model allows additional weak f.f.’s

\[
\langle n|J_\mu^{\text{second class}}|p\rangle = \overline{u}_n \left( F_S q_\mu - \frac{i}{2m} G_T \sigma_{\mu\nu} \gamma_5 q^\nu \right) u_p
\]

Constraints on \( F_S \) and \( G_T \) from \( \mu^- \)-capture on \(^3\text{He}\)—analysis by Gazit (2008) but consistent with present predictions:

\[
F_S = -0.005 \pm 0.68 \quad \quad G_T/G_A = -0.1 \pm 0.68
\]

- Limits on \( F_S \) tighter than from a survey of \( 0^+ \rightarrow 0^+ \beta\)-decays:

\[
F_S = -0.01 \pm 0.27 \quad \quad \text{Severijns et al. (2006)}
\]

- QCD sum rule estimate for tensor f.f.:

\[
G_T/G_A = -0.0152(53) \quad \quad \text{Shiomi (1996)}
\]
Summary and outlook

- Nuclear theory in reasonable agreement with data for suppressed processes
- In some instances, such as $\mu$-capture, it provides predictions with $\lesssim 1\%$ accuracy: extract information on nucleon properties
- Current efforts in $\chi$EFT aimed at:
  1. Completing an independent derivation of the parity-violating (PV) potential at $N^2$LO ($Q$), and an analysis of PV effects in $A=2$, 3, and 4 systems
  2. EM structure of light nuclei: $d(e, e')pn$ at threshold, charge and magnetic form factors, $\ldots$
  3. Including $\Delta$ d.o.f. explicitly in nuclear potentials and currents (to improve convergence)