A=3–4 radiative captures in a hybrid $\chi$EFT approach

- EM currents in the conventional approach
- Potential and EM currents up to one loop in $\chi$EFT
- Boost corrections to the chiral potential
- $^2\text{H}(n, \gamma)^3\text{H}$ and $^3\text{He}(n, \gamma)^4\text{He}$ captures: a first set of calculations in the hybrid approach
- Summary and outlook

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

References: Pastore et al., PRC\textbf{78}, 064002 (2008); PRC\textbf{80}, 034004 (2009);
Girlanda et al., PRC\textbf{81}, 034005 (2010)
Conventional Approach: EM Currents

Marcucci et al., PRC72, 01401 (2005)

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

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

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

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

\[
\mathbf{j}^{(2)}(v) \xrightarrow{\text{long range}} \mathbf{j}^{(2)}(v)
\]
• 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 $S(E_{\text{CM}})$ vs. $E_{\text{CM}}$ in keV and MeV with data points and curves from Griffiths et al., Schmidt et al., Ma et al., and LUNA.]
Nuclear $\chi$EFT Approach


- $\chi$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
Previous Work

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

- **$NN$ potentials:**
  - van Kolck *et al.* (1994–96)
  - Kaiser, Weise *et al.* (1997–98)
  - Entem and Machleidt (2002–03)

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

Lots of work in pionless EFT too …
Preliminaries

- Degrees of freedom: pions ($\pi$) and nucleons ($N$)
- Time-ordered perturbation theory (TOPT):

$$-rac{\hat{e}_{q\lambda}}{\sqrt{2\omega_q}} \cdot j = \langle N'N' \mid T \mid NN; \gamma \rangle$$

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

- $H_0 = \text{free } \pi \text{ and } N \text{ Hamiltonians}; H_1 = \text{interacting } \pi, N, \text{ and } \gamma \text{ Hamiltonians implied by } \mathcal{L}_{\text{eff}}$
- Irreducible and recoil-corrected reducible contributions retained in $T$ expansion
**Power Counting**

- In the chiral expansion the transition amplitude is expressed as
  \[ T = T^{LO} + T^{NLO} + T^{N^2LO} + \ldots, \]
  and \( T^{N^nLO} \sim \left( \frac{Q}{\Lambda \chi} \right)^n T^{LO} \)
  and power counting allows one to arrange contributions to \( T \) in powers of \( Q \)

- A contribution with \( N \) interaction vertices and \( L \) loops scales as
  \[
  e \left( \prod_{i=1}^{N} Q^{\alpha_i-\beta_i/2} \right) \times Q^{-(N-1)} \times Q^{3L}
  \]
  \( \alpha_i = \) number of derivatives (momenta) and \( \beta_i = \) number of \( \pi \)'s at each vertex

- This power counting also follows from considering Feynman diagrams, where loop integrations are in four dimensions
Strong Interaction Vertices up to $Q^2$

\[ H_{\pi NN} = -i \frac{g_A}{F_\pi} \frac{\sigma \cdot k}{\sqrt{2} \omega_k} \tau_a \]
\[ H_{\pi\pi NN} = -i \frac{\omega_{k_1} - \omega_{k_2}}{F_\pi^2 \sqrt{4 \omega_{k_1} \omega_{k_2}}} \epsilon_{abc} \tau_c \]

- $g_A = 1.29$ (via GT-relation) and $F_\pi = 184.8$ MeV

$H_{CT0}$: $4N$ contact terms, 2 LEC’s

$H_{CT2}$: $4N$ contact terms with two gradients, 12 LEC’s
Electromagnetic Interaction Vertices up to $Q^2$

- $H^{(0)}_{\gamma\pi NN}$, $H_{\gamma NN}$, and $H_{\gamma\pi\pi}$ known: depend on $g_A$, $F_\pi$, and proton and neutron $\mu$’s ($\mu_p = 2.793 \mu_N$ and $\mu_n = -1.913 \mu_N$)

- $H_{CT\gamma}$: terms from minimal substitution in $H_{CT2}$ known, but 2 additional LEC’s enter due non-minimal couplings

- $H^{(2)}_{\gamma\pi NN}$ from $\mathcal{L}_{\gamma\pi N}$ of Fettes et al. (1998): depends on 3 LEC’s, two multiplying isovector structures ($\sim \gamma N \Delta$-excitation current) and one isoscalar structure ($\sim \gamma \rho \pi$ transition current)
Two-Body Currents up to $N^2$LO

- Up to $N^2$LO

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

- One-loop corrections to one-body current absorbed into $\mu_N$ and $\langle r_N^2 \rangle$
Two-Body Currents at $N^3\text{LO} \ (eQ^3)$

- One-loop corrections:

- Tree-level current with one $eQ^2$ vertex (3 LEC’s):

- Currents from contact interactions (12 LEC’s from minimal and 2 LEC’s from non-minimal couplings):
Recoil Corrections at N²LO

- N²LO reducible and irreducible contributions in TOPT

\[ j^{N^2\text{LO}} = \text{Reducible} \quad \text{Irreducible} \]

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

\[ \begin{align*}
E_I & \quad \text{Reducible} \quad = \quad v_\pi \left( 1 + \frac{E_i - E_I}{2\omega_\pi} \right) \frac{1}{E_i - E_I} j^{\text{LO}} \\
\quad \text{Irreducible} \quad = \quad -\frac{v_\pi}{2\omega_\pi} j^{\text{LO}}
\end{align*} \]

- Recoil corrections to reducible diagrams cancel irreducible contribution
Recoil Corrections at $N^3$LO

$$j_{N^3LO} = \begin{array}{c}
\begin{array}{c}
\text{Direct} \\
\text{Crossed}
\end{array}
\end{array}$$

- Reducible contributions

$$j_{\text{red}} = \int v^\pi(q_2) \frac{1}{E_i - E_I} j_{NLO}^\pi(q_1)$$

$$-2 \int \frac{\omega_1 + \omega_2}{\omega_1 \omega_2} V_{\pi NN}(2, q_2) V_{\pi NN}(2, q_1) V_{\pi NN}(1, q_2) V_{\gamma \pi NN}(1, q_1)$$

- 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
Magnetic Moment at N^3LO

$$\mu_{\text{Sachs}}^{N^3LO} = -\frac{i}{2} e (\tau_1 \times \tau_2)_z R \times \nabla_k v_0^{2\pi}(k) + \frac{e}{4} \frac{\tau_{1,z} - \tau_{2,z}}{2} R$$
$$\times \left[ 2 (C_2 + C_4 \sigma_1 \cdot \sigma_2) K - i C_5 \frac{\sigma_1 + \sigma_2}{2} \times k \right] + C_7 (\sigma_1 \sigma_2 \cdot K + \sigma_1 \cdot K \sigma_2)$$

$$\mu_{\text{loop}}^{N^3LO} = \frac{e g_A^2}{8 \pi^2 F_4^2} \tau_{2,z} \left[ F_0(k) \sigma_1 - F_2(k) \frac{k \sigma_1 \cdot k}{k^2} \right]$$
$$+ \frac{e g_A^2}{2 \pi^2 F_2^2} \tau_{2,z} \left( C_S \sigma_2 - C_T \sigma_1 \right) + 1 \Leftrightarrow 2$$

$$\mu_{\text{tree}}^{N^3LO} = e \frac{g_A}{F_\pi^2} \left[ (d^Y_1 \tau_{2,z} + d^S_1 \tau_1 \cdot \tau_2) k \right] - d^V_2 (\tau_1 \times \tau_2)_z \sigma_1 \times k \left[ \frac{\sigma_2 \cdot k}{k^2 + m_\pi^2} + 1 \Leftrightarrow 2 \right]$$

$$\mu_{\text{CT}}^{N^3LO} = -e c^S \sigma_1 - e c^V (\tau_{1,z} - \tau_{2,z}) \sigma_1 + 1 \Leftrightarrow 2$$
Comparing to Park et al. (1996) and Kölling et al. (2009)

- Expressions for two-body currents (and potential) at one loop in agreement with those of Bonn group (derived via the UTM)
- Expression for $\mu$ in Park et al. has different isospin structure: different treatment of box diagrams—only irreducible ones retained in Park et al.
Determining LEC’s: \( NN \) Potential at \( N^2 \)LO

- Contact potential at \( N^2 \)LO: \( v^{CT2}(k, K) + v^{CT2}_P(k, K) \)
  - Galilean-invariant term \( v^{CT2} \) depends on 7 LEC’s (\( C_i \)’s)
  - Pair-momentum dependent term \( v^{CT2}_P \) depends on 5 LEC’s:

\[
v^{CT2}_P = iC^*_1 \frac{\sigma_1 - \sigma_2}{2} \cdot P \times k + C^*_2 (\sigma_1 \cdot P \sigma_2 \cdot K - \sigma_1 \cdot K \sigma_2 \cdot P) + (C^*_3 + C^*_4 \sigma_1 \cdot \sigma_2) P^2 + C^*_5 \sigma_1 \cdot P \sigma_2 \cdot P
\]

- Interpretation of \( v^{CT2}_P \): boost correction to LO (rest-frame)
  \( v^{CT0} \), then \( C^*_1 = (C_S - C_T)/(4m^2_N) \), \( C^*_2 = C_T/(2m^2_N) \), ... 

- Retaining recoil corrections in both \( v \) and \( j \) ensures current conservation up to \( N^3 \)LO
Fits to $np$ Phases up to $T_{LAB} = 100$ MeV

LS-equation regulator $\sim \exp(-2Q^4/\Lambda^4)$ with $\Lambda = 500$, 600, and 700 MeV (cutting off momenta $Q \gtrsim 3-4 \, m_\pi$)
OPE+TPE chiral potential in first order PT, after Kaiser et al. (1997): orange dash-double-dot line
### Deuteron Properties

<table>
<thead>
<tr>
<th>$\Lambda$ (MeV)</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>Expt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d$ (MeV)</td>
<td>2.2244</td>
<td>2.2246</td>
<td>2.2245</td>
<td>2.224575(9)</td>
</tr>
<tr>
<td>$\eta_d$</td>
<td>0.0267</td>
<td>0.0260</td>
<td>0.0264</td>
<td>0.0256(4)</td>
</tr>
<tr>
<td>$r_d$ (fm)</td>
<td>1.943</td>
<td>1.947</td>
<td>1.951</td>
<td>1.9734(44)</td>
</tr>
<tr>
<td>$\mu_d$ ($\mu_N$)</td>
<td>0.860</td>
<td>0.858</td>
<td>0.853</td>
<td>0.8574382329(92)</td>
</tr>
<tr>
<td>$Q_d$ (fm$^2$)</td>
<td>0.275</td>
<td>0.272</td>
<td>0.279</td>
<td>0.2859(3)</td>
</tr>
<tr>
<td>$P_D$ (%)</td>
<td>3.44</td>
<td>3.87</td>
<td>4.77</td>
<td></td>
</tr>
</tbody>
</table>
Contact Lagrangian at $Q^2$

Ordóñez et al., PRC **53**, 2086 (1996)

<table>
<thead>
<tr>
<th>$O_i$</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_1$</td>
<td>$(N^\dagger \vec{\nabla} N)^2 + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_2$</td>
<td>$(N^\dagger \vec{\nabla} N) \cdot (N^\dagger \vec{\nabla} N)$</td>
</tr>
<tr>
<td>$O_3$</td>
<td>$(N^\dagger N)(N^\dagger \vec{\nabla}^2 N) + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_4$</td>
<td>$i(N^\dagger \vec{\nabla} N) \cdot (N^\dagger \vec{\nabla} \times \sigma N) + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_5$</td>
<td>$i(N^\dagger N)(N^\dagger \vec{\nabla} \cdot \sigma \times \vec{\nabla} N)$</td>
</tr>
<tr>
<td>$O_6$</td>
<td>$i(N^\dagger \sigma N) \cdot (N^\dagger \vec{\nabla} \times \vec{\nabla} N)$</td>
</tr>
<tr>
<td>$O_7$</td>
<td>$(N^\dagger \sigma \cdot \vec{\nabla} N)(N^\dagger \sigma \cdot \vec{\nabla} N) + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_8$</td>
<td>$(N^\dagger \sigma j \vec{\nabla}^k N)(N^\dagger \sigma k \vec{\nabla}^j N) + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_9$</td>
<td>$(N^\dagger \sigma j \vec{\nabla}^k N)(N^\dagger \sigma j \vec{\nabla}^k N) + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_{10}$</td>
<td>$(N^\dagger \sigma \cdot \vec{\nabla} N)(N^\dagger \vec{\nabla} \cdot \sigma N)$</td>
</tr>
<tr>
<td>$O_{11}$</td>
<td>$(N^\dagger \sigma j \vec{\nabla}^k N)(N^\dagger \vec{\nabla}^j \sigma k N)$</td>
</tr>
<tr>
<td>$O_{12}$</td>
<td>$(N^\dagger \sigma j \vec{\nabla}^k N)(N^\dagger \vec{\nabla}^k \sigma j N)$</td>
</tr>
<tr>
<td>$O_{13}$</td>
<td>$(N^\dagger \vec{\nabla} \cdot \sigma \vec{\nabla}^j N)(N^\dagger \sigma j N) + \text{h.c.}$</td>
</tr>
<tr>
<td>$O_{14}$</td>
<td>$2(N^\dagger \vec{\nabla} \sigma j \cdot \vec{\nabla} N)(N^\dagger \sigma j N)$</td>
</tr>
</tbody>
</table>

$$v_{CT^2}(k, K) = C_1 k^2 + C_2 K^2 + (C_3 k^2 + C_4 K^2) \sigma_1 \cdot \sigma_2 + i C_5 \frac{\sigma_1 + \sigma_2}{2} \cdot K \times k$$

$$+ C_6 \sigma_1 \cdot k \sigma_2 \cdot k + C_7 \sigma_1 \cdot K \sigma_2 \cdot K$$

$$v_{PCT^2}(k, K) = i C_1^* \frac{\sigma_1 - \sigma_2}{2} \cdot P \times k + C_2^* (\sigma_1 \cdot P \sigma_2 \cdot K - \sigma_1 \cdot K \sigma_2 \cdot P)$$

$$+ (C_3^* + C_4^* \sigma_1 \cdot \sigma_2) P^2 + C_5^* \sigma_1 \cdot P \sigma_2 \cdot P$$

Actually, 2 of the $O_i$’s in original set are redundant ...
Relativity Constraints
Girlanda et al., PRC81, 034005 (2010)

- Reparametrization invariance: only 7 independent combinations of $O_i$’s [Epelbaum et al., PRC65, 044001 (2002)]

- What about the other 5 combinations?

Explore constraints that relativity imposes at order $Q^2$ in two ways:

- Write down the most general contact $\mathcal{L}$ up to $Q^2$ and carry out its NR reduction

- Enforce the CR’s between the generators $H$ and $K$ directly in the NR theory within a consistent power counting scheme

Both lead to the same result:

$$C_1^* = \frac{C_S - C_T}{4m^2}, \quad C_2^* = \frac{C_T}{2m^2}, \quad C_3^* = -\frac{C_S}{4m^2}, \quad C_4^* = -\frac{C_T}{4m^2}, \quad C_5^* = 0$$

and $v_p^{LO}$ should be included in calculations of $A > 2$ properties
NR Reduction

Building blocks:

\[
(\psi i \bar{\partial}^\alpha i \bar{\partial}^\beta \cdots \Gamma_A \psi) \partial^\lambda \partial^\mu \cdots (\psi i \bar{\partial}^\sigma i \bar{\partial}^\tau \cdots \Gamma_B \psi)/(2m)^{Nd}
\]

\(\partial\) on whole bilinear is \(\sim Q\); \(\bar{\partial}\) inside bilinear is \(\sim Q^0\) and, in principle, any number of \(\bar{\partial}\) is allowed, however,

i) no two Lorentz indices can be contracted within a bilinear
ii) some of the most problematic terms of the type

\[
(\psi i \bar{\partial}^\mu_1 i \bar{\partial}^\mu_2 \cdots i \bar{\partial}^\mu_n \Gamma_A^\alpha \psi) (\psi i \bar{\partial}^\mu_1 i \bar{\partial}^\mu_2 \cdots i \bar{\partial}^\mu_n \Gamma_B^\alpha \psi)/(2m)^{2n}
\]

do not introduce any new structures for \(n > 1\), since

\[
(\bar{u}_3 \Gamma_A^\alpha u_1) (\bar{u}_4 \Gamma_B^\alpha u_2) [(p_1 + p_3) \cdot (p_2 + p_4)]^n/(2m)^{2n}
\]

and to order \(Q^2\) the \([\ldots]\) can be expanded as

\[
1 + n \left[p_1^2 + p_2^2 + p_3^2 + p_4^2 - (p_1 + p_3) \cdot (p_2 + p_4)\right]/(4m^2)
\]
• 36 hermitian, $C$- and $P$-invariant terms

• NR reduction and use of EOM to remove time derivatives lead to 2 leading terms ($Q^0$), accompanied by specific $1/m^2$ corrections, and 7 subleading ones ($Q^2$)

$$\mathcal{L} = -\frac{1}{2} C_S \left[ O_S + \frac{1}{4m^2}(O_1 + O_3 + O_5 + O_6) \right]$$

$$-\frac{1}{2} C_T \left[ O_T - \frac{1}{4m^2} \left( O_5 + O_6 - O_7 + O_8 + 2O_{12} + O_{14} \right) \right]$$

$$-\frac{1}{2} C_1 (O_1 + 2O_2) + \frac{1}{8} C_2 (2O_2 + O_3) - \frac{1}{2} C_3 (O_9 + 2O_{12})$$

$$-\frac{1}{8} C_4 (O_9 + O_{14}) + \frac{1}{4} C_5 (O_6 - O_5) - \frac{1}{2} C_6 (O_7 + 2O_{10})$$

$$-\frac{1}{16} C_7 (O_7 + O_8 + 2O_{13})$$
Poincaré Algebra Constraints
Girlanda et al., PRC 81, 034005 (2010)

- $H = H_0 + H_I$ and $K = K_0 + K_I$

\[ [K^i, K^j] = -i \epsilon^{ijk} J^k = [K_0^i, K_0^j] \quad [K, H] = i P = [K_0, H_0] \]

- Power counting:

\[
K_0 = K_{(−1)}_0 + K_{(1)}_0 + \ldots \quad H_0 = H_{(0)}_0 + H_{(2)}_0 + \ldots
\]

- Constraints arise on $H_I$ and $K_I$

- In terms of potentials: if $v = v^{\text{LO}} + v^{\text{N2LO}}$ in CM ($P = 0$), then

boost correction is given by

\[
\delta v^{\text{N2LO}}(P) = -\frac{P^2}{8m^2}v^{\text{LO}} + \frac{i}{8m^2} [P \cdot r P \cdot p, v^{\text{LO}}]
\]

\[
+\frac{i}{8m^2} [(\sigma_1 - \sigma_2) \times P \cdot p, v^{\text{LO}}]
\]

Well known: Friar (1975); Carlson et al. (1993)
Nuclear $\chi$EFT (at $Q^2$ and $eQ^3$)

$NN$ potential:

and consistent EM currents:
EM Observables at N³LO

- Pion loop corrections known ($g_A$ and $F_\pi$)
- 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 Δ-resonance saturation
- Three-body currents at N³LO vanish:
Fixing LEC’s in EM Properties of A=2 and A=3 Nuclei
AV18/UIX or N³LO/TNI-N²LO (band)

- $\mu_d$
- $\mu_s(^3\text{He}/^3\text{H})$
- $\mu_v(^3\text{He}/^3\text{H})$

Graph showing the variation of $\mu$ and $\sigma$ with $\Lambda$ (MeV) for different models.
The \( nd \) and \( n^3\text{He} \) Captures

- Suppressed \( M1 \) processes:

<table>
<thead>
<tr>
<th>( n^A(H(n,\gamma)^A) )</th>
<th>( \sigma_{\text{exp}}(\text{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)^3\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. \( \hat{\mu}(\text{IA}) \vert ^3\text{H} \rangle \simeq \mu_p \vert ^3\text{H} \rangle \), since

\[
\vert ^3\text{H} \rangle = \phi(S) \vert (n \downarrow)_1, (n \uparrow)_2, (p \uparrow)_3 \rangle + \ldots
\]

Thus \( \langle nd \vert \hat{\mu}(\text{IA}) \vert ^3\text{H} \rangle \simeq 0 \) 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
Summary and Outlook

- Hybrid predictions for $nd$ ($n^3$He) capture in (reasonable) agreement with exp, and exhibit weak ($\simeq 10\%$) $\Lambda$-dependence

- Future work:
  1. Carry out consistent calculation—based on $\chi$EFT potential and currents—of $A=2$–$4$ EM observables (in progress)
  2. Incorporate boost corrections to chiral potential in calculations of bound and scattering state properties
  3. Extend hybrid studies to different combinations of 2N and 3N potentials and up to $A = 7$ systems (in progress)
  4. Include $\Delta$-isobars in theory (might improve fits to phase shifts and reduce cutoff dependence)