Study of the electroweak processes in the two- and three-nucleon systems with local chiral forces

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Outline

Introduction:
Model of NN interaction
Formalism (states, currents)

Results
$^2$H photodisintegration
nucleon-deuteron radiative capture
$^3$He photodisintegration
muon capture on $^2$H,$^3$He

Outlook
Local chiral forces

New, improved chiral force, presented by Bochum-Bonn group in 2014:

- **All LECs in the long-range part are taken from pion-nucleon scattering without fine tuning**
- **Local regularization in the coordinate space** $V_{lr}(r) \rightarrow V_{lr}(r)f(r)$ with $f(r) \equiv \left(1 - e^{-r^2/R^2}\right)^n$
- $\mathcal{R}=0.8 – 1.2$ fm what corresponds to $\Lambda=330-500$ MeV
- Best $\chi^2/(np$ data up to 300 MeV,) for $\mathcal{R}=0.9$ fm
- Such regularization preserves more long-range OPE and TPE physics
- No (unwanted) short-distance part of TPE force (thus no SFR)
- Very good description of the deuteron properties, phase shifts etc.

  talk by E.Epelbaum

- Very good behaviour for Nd elastic scattering and the deuteron breakup

  talk by H.Witała

Do we see improvement also for electroweak processes?
Our approach (1)


\[ d + \gamma \rightarrow p + n \quad N_{\tau}^{np} = \langle \phi_{np} | (1 + tG_0) j_{\tau} (\tilde{Q}) | \Psi_{\text{deuteron}} \rangle \]

\[ ^3\text{He} + \gamma \rightarrow p + d, \quad ^3\text{He} + \gamma \rightarrow p + p + n, \quad p + d \rightarrow ^3\text{He} + \gamma \]

\[ N_{\tau}^{Nd} = \langle \phi_{Nd} | (1 + P) j_{\tau} (\tilde{Q}) | \Psi_{\text{bound}} \rangle + \langle \phi_{Nd} | P | U \rangle \]

\[ N_{\tau}^{3N} = \langle \phi_0 | (1 + P) j_{\tau} (\tilde{Q}) | \Psi_{\text{bound}} \rangle + \langle \phi_0 | tG_0 (1 + P) j_{\tau} (\tilde{Q}) | \Psi_{\text{bound}} \rangle + \langle \phi_0 | P | U \rangle + \langle \phi_0 | tG_0 P | U \rangle \]

\[ | U \rangle = (tG_0 + 0.5(1 + P)V_{4}^{(1)}G_0(tG_0 + 1))(1 + P) j_{\tau} (\tilde{Q}) | \Psi_{\text{bound}} \rangle + \]

\[ + (tG_0 P + 0.5(1 + P)V_{4}^{(1)}G_0(tG_0 + 1)P) | U \rangle \]

- pd capture transition amplitude can be obtained from two-body \(^3\text{He}\) photodisintegration using time reversal symmetry

- In the following we put \( V_{4}^{(1)} = 0 \)
Our approach (2)

- In the presented here results the Siegert theorem is used as an alternative way to include many-body contributions to the nuclear current. This corresponds to taking into account all electric and magnetic multipoles up to E7 and M7 (more in J.Golak et al. Phys. Rev. C62 (2000) 054005).

- A weak decay of the muonic atoms: $\mu^-d \rightarrow \nu_\mu+n+n$, $\mu^-^3\text{He} \rightarrow \nu_\mu+^3\text{H}$

- The only difference is in the current operator; here we use SNC

$$ j^\lambda (\vec{p}', s'; \vec{p}, s) = \bar{u}(\vec{p}', s') \begin{pmatrix} (g_1^V - 2m g_2^V)\gamma^\lambda \\ + g_2^V (p + p')^\lambda \\ + g_1^A\gamma^\lambda\gamma^5 \\ + g_2^A(p - p')^\lambda\gamma^5 \end{pmatrix} \tau_u(\vec{p}, s) $$

either in the nonrelativistic form or with $1/m^2$ corrections (RC)

The total cross section in the deuteron photodisintegration → improved chiral force works well for this process.
The deuteron tensor analyzing powers $T_{11}(d)$ and $T_{21}(d)$ in the deuteron photodisintegration at 100 MeV photon lab. energies.

→ improved chiral force works well for this process

$LO: \quad \delta X^{(0)} = Q^2 |X^0|$  
$NLO: \quad \delta X^{(2)} = \max (Q^3 |X^0|, Q^4 |\Delta X^{(2)}|)$

$\Delta X^{(2)} = X^{(2)} - X^{(0)}$

$\Delta X^{(i)} = X^{(i)} - X^{(i-1)}$

$N^{(i-1)} LO \quad (i \geq 3): \quad \delta X^{(i)} = \max (Q^{i+1} |X^{(0)}|, Q^{i-1} |\Delta X^{(2)}|, Q^{i-2} |X^{(3)}|)$

$\delta X^{(2)} \geq Q \delta X^{(0)}, \quad \delta X^{(i \geq 3)} \geq Q \delta X^{(i-1)}$
The c.m. neutron-deuteron capture cross section at 9.0 MeV neutron lab. energy. → cut-off dependence much smaller at higher orders also for nd-capture.
The c.m. proton-deuteron capture cross section at: 29.0 MeV and 95 MeV deuteron lab. energies → smaller cut-off dependence at higher energies

OLD
- NN N2LO
- NN N3LO
- Av18+UrbIX
- exp Belt et al, Pitts et al

N4LO
- AV18+UrbIX
- exp Belt et al, Pitts et al
- R=0.8 fm
- R=0.9 fm
- R=1.0 fm
- R=1.1 fm
- R=1.2 fm
The deuteron analyzing power $A_y(d)$ at: a) 17.5, b) 29.0, c) 45 and d) 95 MeV deuteron lab. energies
→ smaller cut-of dependence also for el-mag spin observables

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Total (2body+3body) $^3$He photodisintegration cross section and it’s theoretical uncertainty

$LO:$ \[ \delta X^{(0)} = Q^2 |X^0| \]
$NLO:$ \[ \delta X^{(2)} = \max (Q^3 |X^0|, Q^1 |\Delta X^{(2)}|) \]

$N^{(i-1)}LO$ \( (i \geq 3): \) \[ \delta X^{(i)} = \max (Q^{i+1} |X^{(0)}|, Q^{i-1} |\Delta X^{(2)}|, Q^{i-2} |X^{(3)}|) \]

\[ \delta X^{(2)} \geq Q \delta X^{(0)}, \quad \delta X^{(i \geq 3)} \geq Q \delta X^{(i-1)} \]

$E_\gamma = 12$ MeV

$E_\gamma = 40$ MeV

$E_\gamma = 120$ MeV

$\sigma^{tot}_{\gamma}[fm^2]$
Inclusive three-body $^3$He photodisintegration at $E_\gamma=12$ MeV

R=0.9 fm
Inclusive three-body $^3$He photodisintegration at $E_\gamma=40$ MeV

$R=0.9$ fm

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Inclusive three-body $^3\text{He}$ photodisintegration at $E_\gamma=120$ MeV

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Results for decay of muonic atoms (d and $^3$He)

Doublet capture rates ($F=\frac{1}{2}$) in [s$^{-1}$] for $\mu^-+d \rightarrow \nu_\mu+n+n$ (SNC with RC)

<table>
<thead>
<tr>
<th>Chiral order</th>
<th>R=0.8 fm</th>
<th>R=0.9 fm</th>
<th>R=1 fm</th>
<th>R=1.1 fm</th>
<th>R=1.2 fm</th>
<th>$\Gamma_{\text{max}} - \Gamma_{\text{min}}$</th>
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<tbody>
<tr>
<td>LO</td>
<td>396.0</td>
<td>397.4</td>
<td>398.4</td>
<td>398.9</td>
<td>399.2</td>
<td>3.3</td>
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<tr>
<td>NLO</td>
<td>384.2</td>
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<td>385.2</td>
<td>384.3</td>
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<tr>
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<td>386.1</td>
<td>386.3</td>
<td>385.6</td>
<td>384.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Total capture rates in [s$^{-1}$] for $\mu^-+^3$He $\rightarrow \nu_\mu+^3$H (SNC with RC)

<table>
<thead>
<tr>
<th>Chiral order</th>
<th>R=0.8 fm</th>
<th>R=0.9 fm</th>
<th>R=1 fm</th>
<th>R=1.1 fm</th>
<th>R=1.2 fm</th>
<th>$\Gamma_{\text{max}} - \Gamma_{\text{min}}$</th>
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<td>1618</td>
<td>1610</td>
<td>1594</td>
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<tr>
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<td>1357</td>
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</tr>
</tbody>
</table>


AV18 382.3 s$^{-1}$

AV18 1295 s$^{-1}$

very weak dependence on the regulator parameter R
Summary and Outlook

1. New generation of NN potentials has occurred in 2014

2. First applications to the deuteron and 3He photodisintegrations as well as to muon capture on the deuteron and 3He are very promising

3. Weak dependence on cut-off parameter R

4. Nice convergence with respect to the order of chiral expansion

5. Comparing to old forces, new ones works much better at higher energies

Future:

1. More systematic study (energies, observables) and error estimation
2. Applications to the nuclear structure calculations
3. Inclusion of the 3NF (regularized in the same way)
4. Consistent chiral electromagnetic and weak currents
5. We hope for the precise measurements (ongoing MuSun experiment or the capture rates in the $\mu$-$^3$He break-up channels)
Thank you for your attention