Hadronic parity violation in effective field theory

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Parity-violating nucleon interactions

Nucleon interactions

- Manifestation of interactions between constituents
  - Strong
  - Electromagnetic
  - Weak
- Parity violation in weak interactions
  - Parity-violating component in nucleon interactions
  - Relative strength $\sim G_F m_\pi^2 \approx 10^{-7}$

Weak interactions

- Well-understood between “free” quarks
- Mediated by W, Z exchange $\rightarrow$ range $\sim$ 0.002 fm
- How modified by strong interactions?
- “Inside-out” probe of QCD

Observables

- Isolate PV effects through pseudoscalar observables ($\sigma \cdot p$)
- Interference between PC and PV amplitudes

Complex nuclei

- Enhancement up to 10% effect (^{139}La)
- Theoretically difficult

Two-nucleon system

- $\vec{N}N$ scattering (Bonn, PSI, TRIUMF, LANL)
- $np \leftrightarrow d\gamma$ (SNS, LANSCE, Grenoble, HIGS2?)

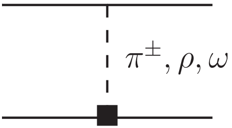
Few-nucleon systems

- $\vec{N}\alpha$ scattering (PSI, NIST)
- ^{3}He$(\vec{n}, p)^3$H (SNS)
- $\vec{n}d \to t\gamma$
- $\ldots$

Meson-exchange model

DDH model

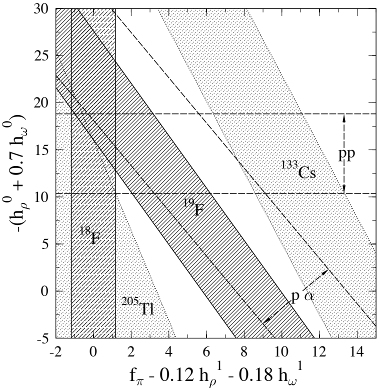
- Weak interaction encoded in PV meson-nucleon couplings
- Single-meson exchange ($\pi^{\pm}, \rho, \omega$) between two nucleons with one strong and one weak vertex



- Estimate weak couplings (quark models, symmetries) $\Rightarrow$ ranges and “best values”
- Has been standard for analyzing experiments

Desplanques, Donoghue, Holstein (1980)

Potential problems



Haxton (2008)

- PV interactions?
- Consistency PC and PV interactions?
- Nuclear structure?

EFT in few-nucleon sector

Effective field theories for PV

One-nucleon sector

- PV πN coupling

Two-nucleon sector

- Pionless theory: *NN* contact interactions
- Explicit pions: *NN* contact interactions and PV πN coupling
- "Hybrid" approach: EFT PV potential combined with phenomenological wave functions

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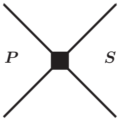
Kaplan, Savage (1993); Savage, Springer (1998); Savage (2001); Zhu, Maekawa, Holstein, Ramsey-Musolf, van Kolck (2005); Liu (2007); Song et al. (2011/12)

Parity violation in EFT($\not\pi$)

Structure of interaction

- Only nucleons
- Contact interactions
- Parity determined by orbital angular momentum $L : (-1)^L$
- Simplest parity-violating interaction: $L \to L \pm 1$
- Leading order: $S - P$ wave transitions



- Spin, isospin: 5 different combinations

Danilov (1965, '71, '72); Phillips, MRS, Springer (2009); Girlanda (2008)

Lowest-order parity-violating Lagrangian

$$\begin{aligned}
\mathcal{L}_{PV} = -\Big[& \mathcal{C}^{(^3S_1-^1P_1)} \left(N^T\sigma_2\,\vec{\sigma}\tau_2 N\right)^\dagger \cdot \left(N^T\sigma_2\tau_2 i\overleftrightarrow{\nabla} N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} \left(N^T\sigma_2\tau_2\vec{\tau}N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot i\overleftrightarrow{\nabla}\tau_2\vec{\tau}N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\,\epsilon^{3ab} \left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\overleftrightarrow{\nabla}\tau_2\tau^b N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\,\mathcal{I}^{ab} \left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot i\overleftrightarrow{\nabla}\tau_2\tau^b N\right) \\
& + \mathcal{C}^{(^3S_1-^3P_1)}\,\epsilon^{ijk} \left(N^T\sigma_2\sigma^i\tau_2 N\right)^\dagger \left(N^T\sigma_2\sigma^k\tau_2\tau_3\overleftrightarrow{\nabla}^j N\right)\Big] \\
& + h.c.
\end{aligned}$$

- Need 5 experimental results to determine LECs
- Notation: $g^{(X-Y)} \propto \mathcal{C}^{(X-Y)}$

Phillips, MRS, Springer (2009)

PV nucleon-nucleon scattering

- Consider asymmetry in $\vec{N}N$ scattering

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$\sigma_\pm$: cross section for $\pm$-helicity beam

$$A_L^{pp/nn} = 8p \frac{\mathcal{A}_{pp/nn}}{\mathcal{C}_0^{^1S_0}}$$

$$\mathcal{A}_{pp} = 4\left(\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\right)$$
$$\mathcal{A}_{nn} = 4\left(\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} - \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\right)$$

- No Coulomb interaction for *pp*; can be included in EFT($\not\pi$): $\sim$ 3 percent at E=13.6 MeV
- Also calculated *np*

Neutron-proton spin rotation

- Perpendicularly polarized beam on unpolarized target
- PV interactions cause spin rotation

$$\frac{1}{\rho}\left.\frac{d\phi^{np}_{PV}}{dL}\right|_{\mathrm{LO+NLO}} = \Bigg([4.5 \pm 0.5] \left(2g^{({}^3S_1-{}^3P_1)} + g^{({}^3S_1-{}^1P_1)}\right) - [18.5 \pm 1.9] \left(g^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} - 2g^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)}\right)\Bigg) \mathrm{rad\ MeV}^{-\frac{1}{2}}$$

- Estimate

$$\left|\frac{d\phi^{np}_{PV}}{dL}\right| \approx \left[10^{-7} \cdots 10^{-6}\right] \frac{\mathrm{rad}}{\mathrm{m}}$$

Grießhammer, MRS, Springer (2012)

Electromagnetic processes: $np \to d\gamma$

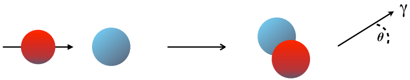
Invariant amplitude for $np \to d\gamma$

$$
\begin{aligned}
\mathcal{M} =& eXN^T\tau_2\sigma_2\left[\boldsymbol{\sigma}\cdot\boldsymbol{q}\,\boldsymbol{\epsilon}_d^*\cdot\boldsymbol{\epsilon}_\gamma^* - \boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}_\gamma^*\,\boldsymbol{q}\cdot\boldsymbol{\epsilon}_d^*\right]N \\
&+ ieY\epsilon^{ijk}{\boldsymbol{\epsilon}_d^*}^i\boldsymbol{q}^j{\boldsymbol{\epsilon}_\gamma^*}^k\left(N^T\tau_2\tau_3\sigma_2N\right) \\
&+ ieW\epsilon^{ijk}{\boldsymbol{\epsilon}_d^*}^i{\boldsymbol{\epsilon}_\gamma^*}^k\left(N^T\tau_2\sigma_2\sigma^jN\right) \\
&+ eV\boldsymbol{\epsilon}_d^*\cdot\boldsymbol{\epsilon}_\gamma^*\left(N^T\tau_2\tau_3\sigma_2N\right) + \dots
\end{aligned}
$$

- X, Y: parity-conserving amplitudes
- V, W: parity-violating amplitudes

Kaplan et al. (1999)

Electromagnetic processes: $\vec{n}p \to d\gamma$



$\vec{n}p \to d\gamma$

- Quantity of interest

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$$

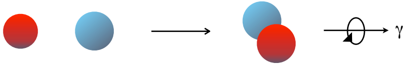
-

$$A_\gamma = -2\frac{M}{\gamma^2}\frac{\mathrm{Re}[Y^* W]}{|Y|^2} = \frac{32}{3}\frac{M}{\kappa_1(1-\gamma a^{^1S_0})}\frac{\mathcal{C}^{(^3S_1-^3P_1)}}{\mathcal{C}_0^{(^3S_1)}}$$

- Experiment: Currently consistent with zero
- NPDGamma @ SNS: A_γ to 10^{-8}

Savage (2001); MRS, Springer (2009)

Electromagnetic processes: $np \to d\vec{\gamma}$



Circular polarization

- Quantity of interest

$$P_\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

-

$$P_\gamma = 2\frac{M}{\gamma^2}\frac{\mathrm{Re}[Y^* V]}{|Y|^2}$$

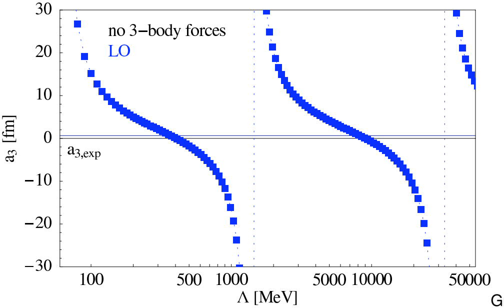
$$\sim a\frac{\mathcal{C}^{(^3S_1-^1P_1)}}{\mathcal{C}_0^{(^3S_1)}} + b\frac{\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}}{\mathcal{C}_0^{(^1S_0)}}$$

- Information complementary to $\vec{n}p \to d\gamma$
- Experimental result $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$
- At threshold: $P_\gamma = A_L^\gamma$ in $\vec{\gamma}d \to np$: opportunity for HIGS2?

MRS, Springer (2009); Knyazkov et al. (1983); http://www.tunl.duke.edu/higs2.php

Three-nucleon interaction

- EFT estimates relative sizes of 3N, 4N, ... interactions
- Dimensional analysis: $|2N| > |3N| > |4N| > \ldots$
- *nd* scattering in $^2S_{\frac{1}{2}}$ channel: scattering length a_3 vs cutoff



Grießhammer

- Three-body counterterm at leading order
- Fixed from data: a_3, triton binding energy, ...

Danilov (1961); Bedaque, Hammer, van Kolck (2000)

PV three-body operators

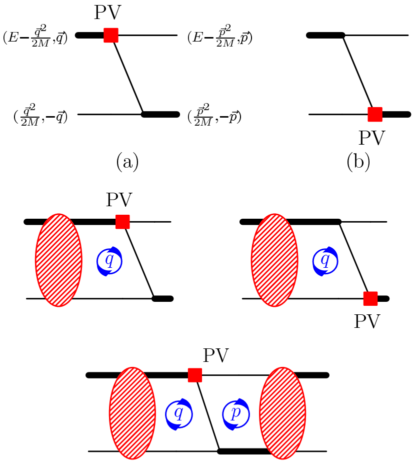
- PV three-body operators required for renormalization?
- Additional experimental input?
- PV *Nd* scattering
  - No divergence at LO
  - Spin-isospin structure of PV 3N operators at NLO different from possible divergence structure
  - Cancellation from diagrams with PC 3N operators

No PV three-body operator at LO and NLO

Grießhammer, MRS (2010)

PV $\vec{n}d$ scattering

- $\vec{n}d$ forward scattering with one PV insertion
- At LO: tree-level, "one-loop," "two-loop" diagrams:



Grießhammer, MRS, Springer (2012); Vanasse (2011); Schiavilla et al. (2008/11)

Neutron-deuteron spin rotation at NLO

- Spin-rotation angle at NLO

$$\frac{1}{\rho}\,\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L} = \Big([8.0 \pm 0.8]\; g^{({}^3S_1-{}^1P_1)} \;-\; [18.3 \pm 1.8]\; g^{({}^3S_1-{}^3P_1)}$$

$$+\; [2.3 \pm 0.5]\;\Big(3g^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} - 2g^{({}^1S_0-{}^3P_0)}_{(\Delta I=1)}\Big)\Big)\text{rad MeV}^{-\frac{1}{2}}$$

- Estimate

$$\left|\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L}\right| \approx \left[10^{-7}\cdots 10^{-6}\right]\;\frac{\text{rad}}{\text{m}}$$

Grießhammer, MRS, Springer (2012)

Other three- and few-nucleon observables

Three-nucleon observables

- $\vec{n}d \to t\gamma$
- $\vec{\gamma}\,{}^3\mathrm{He} \to pd$

Few-nucleon observables

- ${}^3\mathrm{He}(\vec{n},p){}^3\mathrm{H}$
- $\vec{n}\alpha$ spin rotation
- $\vec{p}\alpha$ scattering

Consistent few-body EFT calculations up to $A = 5$ desirable

Song et al. (2012); Viviani et al. (2010)

Parity violation in pionful EFT

- At higher energies and/or larger A: explicit pion dof needed
- Lowest-order PV πN Lagrangian:

$$\mathcal{L}^{\text{PV}} = \frac{h_\pi F}{2\sqrt{2}} \bar{N} X_-^3 N + \ldots$$
$$= i h_\pi \left(\pi^+ \bar{p} n - \pi^- \bar{n} p \right) + \ldots$$

- PV in Compton scattering and pion production on the nucleon
- Pion-exchange contributions to *NN* potential

Kaplan, Savage (1993); Chen, Ji (2001); Zhu et al. (2001)

Conclusion & Outlook

Hadronic parity violation

- Probe of non-perturbative QCD phenomena (“inside-out)
- Few-body sector theoretically cleaner
- Challenging experiments, but doable $\rightarrow$ see talk by M. Gericke

EFT for parity-violating *NN* interactions

- 5 independent operators at LO in EFT($\not\pi$)
- No PV 3-body operators at LO and NLO
- Consistent calculations in two-, three-, and few-body sectors
- Lattice $\rightarrow$ see talk by J. Wasem

Wasem (2011); Tiburzi (2012)