Hadronic parity violation in effective field theory

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Hadronic parity violation

Parity violation in pionless EFT

Parity violation in chiral EFT

Conclusion & Outlook
Hadronic parity violation

- Parity-violating component in hadronic interactions
- Relative strength for $NN$ case: $\sim G_F m^2_{\pi} \approx 10^{-7}$
- Origin: weak interaction between quarks
  - $W, Z$ exchange
  - Range $\sim 0.002$ fm
- How manifested for quarks confined in nucleon?
  - Interplay of weak and nonperturbative strong interactions
  - Sensitive to quark-quark correlations inside nucleon
  - “Inside-out” probe
Observables

Isolate PV effects through pseudoscalar observables \((\vec{\sigma} \cdot \vec{p})\)
- Interference between PC and PV amplitudes
- Longitudinal asymmetries
- Angular asymmetries
- \(\gamma\) circular polarization
- Spin rotation
- Anapole moment

Heavy nuclei
- Enhancement up to 10% effect \((^{139}\text{La})\)
- Theoretically complex
Two-nucleon system
- $\vec{p}p$ scattering (Bonn, PSI, TRIUMF, LANL)
- $\vec{n}p \rightarrow d\gamma$ (SNS, LANSCE, Grenoble)
- $\vec{\gamma}d \leftrightarrow np?$ (HIGS2?)
- $\vec{n}p$ spin rotation?

Few-nucleon systems
- $\vec{n}\alpha$ spin rotation (NIST)
- $\vec{p}\alpha$ scattering (PSI)
- $^3\text{He}(\vec{n}, p)^3\text{H}$ (SNS)
- $\vec{n}d \rightarrow t\gamma$?
- $\vec{\gamma}^3\text{He} \rightarrow pd?$
- $\vec{n}d$ spin rotation?
Parity violation in EFT(\mathcal{\not}F)

Structure of interaction
- At very low energies: pion exchange not resolved
- Only nucleons as explicit degrees of freedom
- Contact terms with increasing number of derivatives
- Parity determined by orbital angular momentum \( L : (-1)^L \)
- Simplest parity-violating interaction: \( L \rightarrow L \pm 1 \)
- Leading order: \( S - P \) wave transitions

- Spin, isospin: 5 different combinations

Lowest-order parity-violating Lagrangian

Partial wave basis

\[ \mathcal{L}_{PV} = - \left[ g^{(3S_1-1P_1)} d_t^{i\dagger} \left( N^T \sigma_2 \tau_2 i D_i N \right) + g^{(1S_0-3P_0)} d_s^{A\dagger} \left( N^T \sigma_2 \vec{\sigma} \cdot \tau_2 \tau_A i D N \right) + g^{(1S_0-3P_0)} \epsilon^{3AB} d_s^{A\dagger} \left( N^T \sigma_2 \vec{\sigma} \cdot \tau_2 \tau^B i D N \right) + g^{(1S_0-3P_0)} \mathcal{I}^{AB} d_s^{A\dagger} \left( N^T \sigma_2 \vec{\sigma} \cdot \tau_2 \tau^B i D N \right) + g^{(3S_1-3P_1)} \epsilon^{ijk} d_t^{i\dagger} \left( N^T \sigma_2 \sigma^k \tau_2 \tau_3 D^j N \right) \right] + \text{h.c.} \]

- Need 5 experimental results to determine LECs

Electromagnetic processes: $np \leftrightarrow d\gamma$

Invariant amplitude for $np \rightarrow d\gamma$

\[
\mathcal{M} = eX N^T \tau_2 \sigma_2 \left[ \vec{\sigma} \cdot \vec{q} \; \epsilon_d^* \cdot \epsilon_\gamma^* - \vec{\sigma} \cdot \epsilon_\gamma^* \; \vec{q} \cdot \epsilon_d^* \right] N \\
+ i e Y \epsilon^{ijk} \epsilon_d^* \epsilon_\gamma^* \left( N^T \tau_2 \tau_3 \sigma_2 N \right) + e E_1 \epsilon N^T \sigma_2 \vec{\sigma} \cdot \epsilon_d^* \tau_2 \tau_3 N \vec{p} \cdot \epsilon_\gamma^* \\
+ i e W \epsilon^{ijk} \epsilon_d^* \epsilon_\gamma^* \left( N^T \tau_2 \sigma_2 \sigma_2 N \right) + e V \epsilon_d^* \cdot \epsilon_\gamma^* \left( N^T \tau_2 \tau_3 \sigma_2 N \right) \\
+ i e U_1 \epsilon^{ijk} \epsilon_d^* \epsilon_\gamma^* \epsilon_d^* k^i \left( N^T \sigma_2 \vec{\sigma} \cdot \vec{p} \tau_2 \tau_3 N \right) \\
+ i e U_2 \epsilon^{ijk} \left( \vec{k} \cdot \epsilon_d^* \epsilon_\gamma^* i^j - \epsilon_\gamma^* \cdot \epsilon_d^* k^i \right) p^j N^T \sigma_2 \sigma_k \tau_2 \tau_3 N + \cdots
\]

- $X$, $E_1$, $Y$: parity-conserving amplitudes
- $V$, $W$, $U_1$, $U_2$: parity-violating amplitudes
- Expansion of each amplitude: $Y = Y_{LO} + Y_{NLO} + \cdots$, etc

Polarized capture: $\vec{n}p \rightarrow d\gamma$

- Polarized neutron capture

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

$$A_\gamma = -2 \frac{M}{\gamma^2} \frac{\text{Re}[Y^* W]}{|Y|^2}$$

$$= \frac{4}{3} \sqrt{\frac{2}{\pi}} \frac{M_2^3}{\kappa_1} \frac{g^{(3S_1-3P_1)}}{(1 - \gamma a^1S_0)}$$

- NPDGamma @ SNS: $A_\gamma$ to $\sim 10^{-8}$ $\rightarrow$ Soon!

See plenary talk by Barrón-Palos (Tuesday, June 30)

Savage (2001); MRS, Springer (2009)
Circular polarization in $np \rightarrow d\gamma$ at threshold

Circular polarization

- Circular polarization

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

$$= \frac{2M \text{Re}[Y^* V]}{\gamma^2 \vert Y \vert^2}$$

$$\sim c_1 g^{(3S_1-1P_1)} + c_2 \left( g^{(1S_0-3P_0)} - 2g^{(1S_0-3P_0)} \right)$$

- Information complementary to $\bar{n}p \rightarrow d\gamma$

- Experimental result $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$

- Related to $A_L^\gamma$ in $\gamma d \rightarrow np$

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Measure at upgraded HIGS facility?

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MRS, Springer (2009); Knyazkov et al. (1983)
$A^\gamma_L$ in $\bar{\gamma}d \rightarrow np$ beyond threshold

$$A^\gamma_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$= 2 \frac{M_N}{(\vec{p}^2 + \gamma^2_t)} |Y|^2 + |E_1v|^2 \frac{M_N^2 \vec{p}^2}{(\vec{p}^2 + \gamma^2_t)^2} \left[ \text{Re}[Y^* V] + 2\text{Re}[X^* W] + \frac{1}{3} \vec{p}^2 \text{Re}[E_1^* v(U_1 + 2U_2)] + \ldots \right]$$

Vanasse, MRS (2014)
$\gamma_L$ in EFT(\not \pi): NLO results

- Fix PV couplings to model estimates
- “Reasonable ranges:” $\gamma_L$ varies over orders of magnitude and sign
Where to measure?

- \( A_L^{\gamma} \) max at threshold \( \Rightarrow \) low count rate
- Simplified figure of merit \( (A_L^{\gamma})^2 \times \sigma(\gamma d \rightarrow np) \)

- Maximized for \( \omega \approx [2.259, 2.264] \) MeV
Three-nucleon interaction

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

- Three-body counterterm at *leading* order
- Fixed from data: $a_3$, triton binding energy, ...
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
PV $\bar{n}d$ scattering

- $\bar{n}d$ 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

\[
\frac{1}{\rho} \frac{d\phi^{nd}_{PV}}{dL} = \left( [8.0 \pm 0.8] g^{(3S_1-1P_1)} - [18.3 \pm 1.8] g^{(3S_1-3P_1)} \right) \\
+ [2.3 \pm 0.5] \left( 3g^{(1S_0-3P_0)}_{(\Delta I=0)} - 2g^{(1S_0-3P_0)}_{(\Delta I=1)} \right) \text{rad MeV}^{-\frac{1}{2}}
\]

- Estimate

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

Grießhammer, MRS, Springer (2012)
Parity violation in chiral EFT

- At higher energies and/or larger $A$: explicit pion dof needed
- Lowest-order PV $\pi N$ Lagrangian:

\[ \mathcal{L}^{\text{PV}} = \frac{h_\pi F}{2\sqrt{2}} \bar{N}X_3^3 N + \ldots \]

\[ = i h_\pi (\bar{p} \pi^+ n - \bar{n} \pi^- p) + \ldots \]

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

Kaplan, Savage (1993); Bedaque, Savage (2000); Chen, Ji (2001); Zhu et al. (2001)
Chiral PV $NN$ potential

- $\mathcal{O}(Q^{-1})$: 
  - One-pion exchange $\propto h_\pi$

- $\mathcal{O}(Q^1)$: 
  - Contact terms analogous to EFT($\pi$) 
  - Two-pion exchange $\propto h_\pi$ 
  - New $\gamma_\pi NN$ contact interaction

Caveat: Assumed $h_\pi$ not “small”
Select applications

$\vec{p}p$ scattering
- Barton’s theorem $\Rightarrow$ No OPE contribution
- TPE $\Rightarrow$ Asymmetry $\propto a_0 h_\pi + a_1 C$
- Fitted value: $h_\pi = (1.1 \pm 2) \times 10^{-6}$

$\vec{n}p \rightarrow d\gamma$
- $a_\gamma = (-0.11 \pm 0.5) \times h_\pi + (0.055 \pm 0.025) \times \bar{C}$
- Constraint from upcoming NPDGamma result

$\vec{n}^3\text{He} \rightarrow p^3\text{H}$
- Chiral PC and PV potentials
- $a_z = a_0 h_\pi + a_1 C_1 + a_2 C_2 + a_3 C_3 + a_4 C_4 + a_5 C_5$
- $|a_0| > |a_2|, |a_3|, |a_4| > |a_1|, |a_5|$
- Ongoing measurement at SNS $\Rightarrow$ see talk by M. Gericke

Kaplan et al. (1999); De Vries et al. (2013,14,15); Viviani et al. (2014)
PV on the lattice

- Determine PV couplings on lattice
- PV quark operators on lattice

\[ h_\pi = \left( 1.099 \pm 0.505 \, \text{(stat.)} \pm^{0.058}_{-0.064} \, \text{(syst.)} \right) \times 10^{-7} \]

- \( m_\pi \sim 389 \, \text{MeV}, \ L \sim 2.5 \, \text{fm}, \ a_s \sim 0.123 \, \text{fm} \)
- Connected diagrams only
- Consistent with most model estimates, lower end of DDH "reasonable range"

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(a) (b) (c)

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Wasem (2012)
Conclusion & Outlook

- Interplay of strong and weak interaction
- Unique probe of nonperturbative strong interactions
- High-intensity sources
  - Low energies
  - Few-nucleon systems
- At very low energies: 5 couplings
- Consistent calculations in few-nucleon systems required
- Chiral PV EFT: inclusion of pions and PV $\pi N$ couplings
- Lattice QCD: preliminary result for PV $\pi N$ coupling $h_\pi$