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: $\sim G_F m_\pi^2 \approx 10^{-7}$
- 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
- γ circular polarization
- Spin rotation
- Anapole moment

Heavy nuclei

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

Two-nucleon system

- $\vec{p}p$ scattering (Bonn, PSI, TRIUMF, LANL)
- $\vec{n}p \to d\gamma$ (SNS, LANSCE, Grenoble)
- $\vec{\gamma}d \leftrightarrow np$? (HIGS2?)
- $\vec{n}p$ spin rotation?

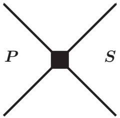
Few-nucleon systems

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

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

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: $L \to L \pm 1$
- Leading order: $S - P$ wave transitions



- Spin, isospin: 5 different combinations

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

Lowest-order parity-violating Lagrangian

Partial wave basis

$$
\begin{aligned}
\mathcal{L}_{PV} = -\Big[& g^{(^3S_1 - ^1P_1)} d_t^{i\dagger} \left(N^T \sigma_2 \tau_2 \, i \overleftrightarrow{D}_i N \right) \\
& + g^{(^1S_0 - ^3P_0)}_{(\Delta I = 0)} d_s^{A\dagger} \left(N^T \sigma_2 \, \vec{\sigma} \cdot \tau_2 \tau_A \, i \overleftrightarrow{D} N \right) \\
& + g^{(^1S_0 - ^3P_0)}_{(\Delta I = 1)} \, \epsilon^{3AB} \, d_s^{A\dagger} \left(N^T \sigma_2 \, \vec{\sigma} \cdot \tau_2 \tau^B \overleftrightarrow{D} N \right) \\
& + g^{(^1S_0 - ^3P_0)}_{(\Delta I = 2)} \, \mathcal{I}^{AB} \, d_s^{A\dagger} \left(N^T \sigma_2 \, \vec{\sigma} \cdot \tau_2 \tau^B \, i \overleftrightarrow{D} N \right) \\
& + g^{(^3S_1 - ^3P_1)} \, \epsilon^{ijk} \, d_t^{i\dagger} \left(N^T \sigma_2 \sigma^k \tau_2 \tau_3 \overleftrightarrow{D}^j N \right) \Big] + \text{h.c.}
\end{aligned}
$$

- Need 5 experimental results to determine LECs

Phillips, MRS, Springer (2009)

Electromagnetic processes: $np \leftrightarrow d\gamma$

Invariant amplitude for $np \to d\gamma$

$$\begin{aligned}\mathcal{M} =& eXN^T\tau_2\sigma_2\left[\vec{\sigma}\cdot\vec{q}\,\boldsymbol{\epsilon}_d^*\cdot\boldsymbol{\epsilon}_\gamma^* - \vec{\sigma}\cdot\boldsymbol{\epsilon}_\gamma^*\,\vec{q}\cdot\boldsymbol{\epsilon}_d^*\right]N \\ &+ ieY\epsilon^{ijk}{\boldsymbol{\epsilon}_d^*}^i\vec{q}^j{\boldsymbol{\epsilon}_\gamma^*}^k\left(N^T\tau_2\tau_3\sigma_2N\right) + eE1_vN^T\sigma_2\vec{\sigma}\cdot\boldsymbol{\epsilon}_d^*\tau_2\tau_3N\vec{p}\cdot\boldsymbol{\epsilon}_\gamma^* \\ &+ ieW\epsilon^{ijk}{\boldsymbol{\epsilon}_d^*}^i{\boldsymbol{\epsilon}_\gamma^*}^k\left(N^T\tau_2\sigma_2\sigma^jN\right) + eV\boldsymbol{\epsilon}_d^*\cdot\boldsymbol{\epsilon}_\gamma^*\left(N^T\tau_2\tau_3\sigma_2N\right) \\ &+ ieU_1\epsilon^{ijk}k^i{\boldsymbol{\epsilon}_\gamma^*}^j{\boldsymbol{\epsilon}_d^*}^kN^T\sigma_2\vec{\sigma}\cdot\vec{p}\tau_2\tau_3N \\ &+ ieU_2\epsilon^{ijk}(\vec{k}\cdot\boldsymbol{\epsilon}_d^*{\boldsymbol{\epsilon}_\gamma^*}^i - \boldsymbol{\epsilon}_\gamma^*\cdot\boldsymbol{\epsilon}_d^*k^i)p^jN^T\sigma_2\sigma_k\tau_2\tau_3N + \cdots\end{aligned}$$

- $X, E1_v, Y$: parity-conserving amplitudes
- V, W, U_1, U_2: parity-violating amplitudes
- Expansion of each amplitude: $Y = Y_{LO} + Y_{NLO} + \cdots$, etc

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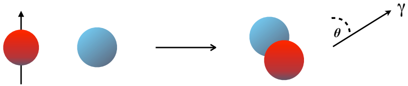
Kaplan, Savage, Springer, Wise (1999), Vanasse, MRS (2014)

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



- Polarized neutron capture

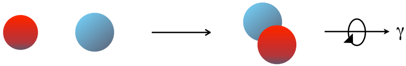
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$$

$$A_\gamma = -2\frac{M}{\gamma^2}\frac{\mathrm{Re}[Y^* W]}{|Y|^2}$$
$$= \frac{4}{3}\sqrt{\frac{2}{\pi}}\frac{M^{\frac{3}{2}}}{\kappa_1\left(1-\gamma a^{{}^1S_0}\right)} g^{({}^3S_1 - {}^3P_1)}$$

- NPDGamma @ SNS: A_γ to $\sim 10^{-8} \to$ Soon!
  See plenary talk by Barrón-Palos (Tuesday, June 30)

Savage (2001); MRS, Springer (2009)

Circular polarization in $np \to d\vec{\gamma}$ at threshold



Circular polarization

- Circular polarization

$$P_\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$
$$= 2\frac{M}{\gamma^2}\frac{\mathrm{Re}[Y^* V]}{|Y|^2}$$
$$\sim c_1\, g^{(^3S_1-^1P_1)} + c_2 \left(g^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2g^{(^1S_0-^3P_0)}_{(\Delta I=2)} \right)$$

- Information complementary to $\vec{n}p \to d\gamma$
- Experimental result $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$
- Related to A_L^γ in $\vec{\gamma}d \to np$

Measure at upgraded HIGS facility?

MRS, Springer (2009); Knyazkov et al. (1983)

A_L^γ in $\vec{\gamma} d \to np$ beyond threshold

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

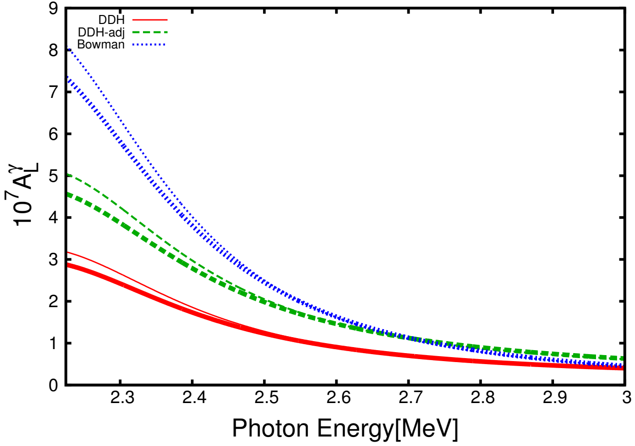
$$= 2\frac{M_N}{(\vec{p}^{\,2} + \gamma_t^2)} \frac{1}{|Y|^2 + |E1_v|^2 \frac{M_N^2 \vec{p}^{\,2}}{(\vec{p}^{\,2}+\gamma_t^2)^2}} \Bigg[\mathrm{Re}[Y^* V] + 2\mathrm{Re}[X^* W]$$

$$+ \frac{1}{3}\vec{p}^{\,2}\mathrm{Re}[E1_v^*(U_1 + 2U_2)] + \dots \Bigg]$$

Vanasse, MRS (2014)

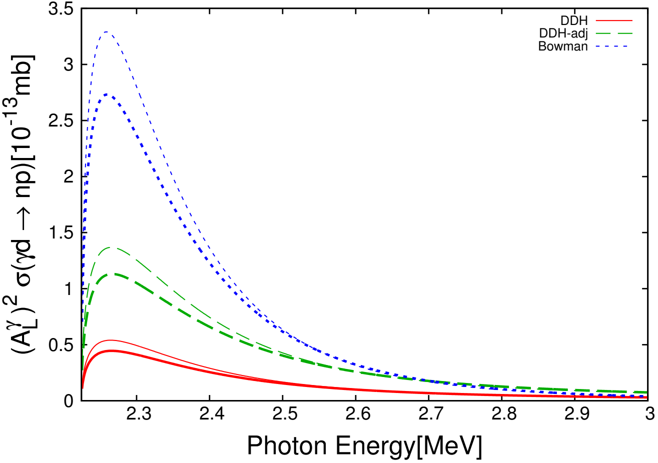
A_L^γ in EFT($\not\pi$): NLO results

- Fix PV couplings to model estimates
- "Reasonable ranges:" A_L^γ varies over orders of magnitude and sign



Where to measure?

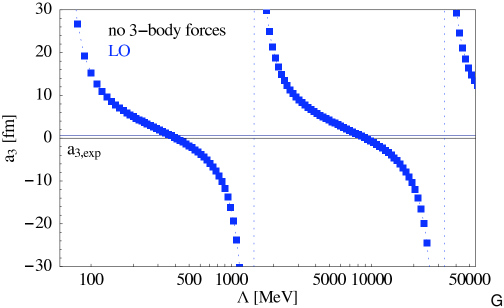
- A_L^γ max at threshold $\Rightarrow$ low count rate
- Simplified figure of merit $(A_L^\gamma)^2 \times \sigma(\gamma d \to np)$



- Maximized for $\omega \approx [2.259, 2.264]$ MeV

Three-nucleon interaction

- EFT estimates relative sizes of 3N, 4N, . . . interactions
- Dimensional analysis: $|2N| > |3N| > |4N| > \ldots$
- *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

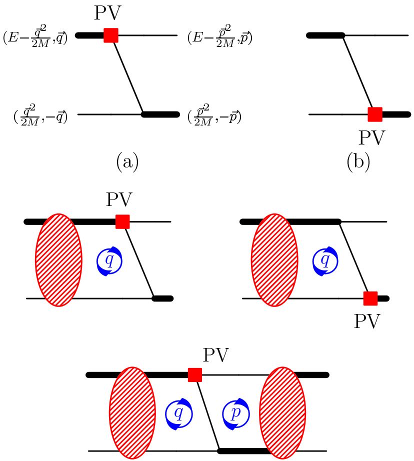
- PV three-body operators required for renormalization?
- Additional experimental input?
- PV *Nd* scattering
  - No divergence at LO
  - Spin-isospin structure of PV 3N operators at NLO different from possible divergence structure
  - Cancellation from diagrams with PC 3N operators

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

$$\frac{1}{\rho}\,\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L} = \Big([8.0\pm0.8]\,g^{(^3S_1-^1P_1)} - [18.3\pm1.8]\,g^{(^3S_1-^3P_1)} + [2.3\pm0.5]\,\Big(3g^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2g^{(^1S_0-^3P_0)}_{(\Delta I=1)}\Big)\Big)\,\mathrm{rad\ MeV}^{-\frac{1}{2}}$$

- Estimate

$$\left|\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L}\right| \approx \left[10^{-7}\cdots10^{-6}\right]\ \frac{\mathrm{rad}}{\mathrm{m}}$$

Grießhammer, MRS, Springer (2012)

Parity violation in chiral EFT

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

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

- 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($\not\pi$)
  - Two-pion exchange $\propto h_\pi$
  - New $\gamma\pi NN$ contact interaction

Caveat: Assumed h_π not "small"

Savage, Springer (1998); Kaplan et al. (1999); Zhu et al. (2005); Viviani et al. (2014); De Vries et al. (2014)

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

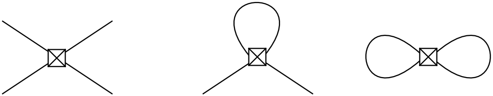
$\vec{n}\,^3\mathrm{He} \rightarrow p\,^3\mathrm{H}$

- 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
- $$h_\pi = \left(1.099 \pm 0.505\ (\text{stat.})\ {}^{+0.058}_{-0.064}\ (\text{syst.})\right) \times 10^{-7}$$
- $m_\pi \sim 389\,\text{MeV}$, $L \sim 2.5\,\text{fm}$, $a_s \sim 0.123\,\text{fm}$
- Connected diagrams only
- Consistent with most model estimates, lower end of DDH "reasonable range"



(a) (b) (c)

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 πN couplings
- Lattice QCD: preliminary result for PV πN coupling h_π