Hadronic parity violation in few-nucleon systems

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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 ~ 0.002 fm
  - How manifested for quarks confined in nucleon?
- Interplay of weak and nonperturbative strong interactions
  - Sensitive to quark-quark correlations inside nucleon
  - No need for high-energy probe
  - "Inside-out probe"
- Isospin dependence? ($\rightarrow \Delta I = 1/2$ puzzle)

Observables

Isolate PV effects through pseudoscalar observables ($\sigma \cdot p$)

- Longitudinal, angular asymmetries
- γ circular polarization
- Spin rotation

Complex nuclei

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

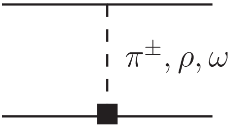
Two- and few-nucleon system

- $\vec{p}p$ scattering
- $np \leftrightarrow d\gamma$
- $\vec{n}\alpha$ spin rotation (NIST)
- $\vec{p}\alpha$ scattering (PSI)
- $^3\text{He}(\vec{n}, p)^3\text{H}$ (SNS)

Meson-exchange model

DDH model

- Single-meson exchange ($\pi^{\pm}, \rho, \omega$) with one strong and one weak vertex



- Weak interaction encoded in 7 PV meson-nucleon couplings
- Estimate weak couplings (quark models, symmetries) $\Rightarrow$ ranges and “best values”
- Combined with variety of PC potentials
- Extensions to include two-pion exchange, Δ,...
- Has been standard for analyzing experiments

Desplanques, Donoghue, Holstein (1980)

Experimental prospects

Ongoing and planned experiments

- High-intensity neutron & photon sources
- Very low energies (cold neutrons, . . .)
- Few-nucleon systems

Theory wishlist

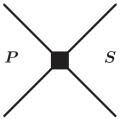
- Suited for low-energy processes
- Model independent
- Consistent treatment of PC + PV interactions + currents

Effective field theory approach

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

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)

PV nucleon-nucleon scattering

- Polarized beam on unpolarized target

$$A_L^{pp/nn} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$
$$= -\sqrt{\frac{32M}{\pi}}\, p \left(g_{(\Delta I=0)}^{(^1S_0-^3P_0)} \pm g_{(\Delta I=1)}^{(^1S_0-^3P_0)} + g_{(\Delta I=2)}^{(^1S_0-^3P_0)} \right)$$

- Coulomb effects $\sim$ 3% at 13.6 MeV

Phillips, MRS, Springer (2009)

Neutron-proton spin rotation

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

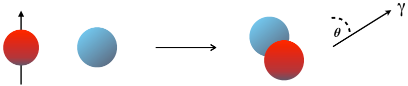
$$\frac{1}{\rho}\,\frac{\mathrm{d}\phi^{np}_{\mathrm{PV}}}{\mathrm{d}L}\bigg|_{\mathrm{LO+NLO}} = \Bigg([4.5\pm 0.5]\,\left(2g^{({}^3S_1-{}^3P_1)} + g^{({}^3S_1-{}^1P_1)}\right) - [18.5\pm 1.9]\,\left(g^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} - 2g^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)}\right)\Bigg)\mathrm{rad\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

- Estimate

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

Grießhammer, MRS, Springer (2012)

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



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

- Quantity of interest

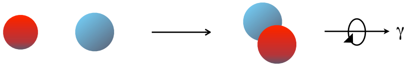
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$$

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

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

Savage (2001); MRS, Springer (2009)

Induced circular polarization: $np \to d\vec{\gamma}$



Circular polarization

- Quantity of interest

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

-

$$P_\gamma \sim c_1\, g^{({}^3S_1 - {}^1P_1)} + c_2 \left(g^{({}^1S_0 - {}^3P_0)}_{(\Delta I=0)} - 2g^{({}^1S_0 - {}^3P_0)}_{(\Delta I=2)} \right)$$

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

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

Breakup: $\vec{\gamma} d \to np$

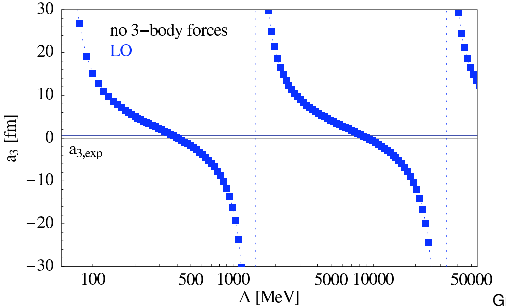
- For reversed kinematics: $P_\gamma = A_L^\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
- Flagship experiment at possible HIγS intensity upgrade
- Model calculation:
  - AV18+DDH or CD-Bonn+DDH
  - Two different PV parameter sets
  - At $\omega = 2.2259$ MeV

Bonn+DDH-adj	AV18+DDH-adj	AV18+DDH
9.05×10^{-8}	5.19×10^{-8}	2.38×10^{-8}

http://www.tunl.duke.edu/higs2.php; Schiavilla et al. (2004)

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



- 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

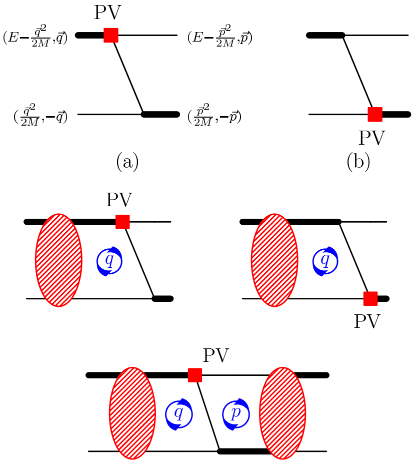
No PV three-body operator at LO and NLO

- Verified numerically

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

$$\frac{1}{\rho}\,\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L} = \Big([8.0\pm 0.8]\; g^{(^3S_1-{}^1P_1)} \;-\; [18.3\pm 1.8]\; g^{(^3S_1-{}^3P_1)}$$
$$+\;[2.3\pm 0.5]\;\Big(3g^{(^1S_0-{}^3P_0)}_{(\Delta I=0)} - 2g^{(^1S_0-{}^3P_0)}_{(\Delta I=1)}\Big)\Big)\mathrm{rad\;MeV}^{-\frac{1}{2}}$$

- Estimate

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

Grießhammer, MRS, Springer (2012)

Other three- and few-nucleon observables

Three-nucleon observables

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

Few-nucleon observables

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

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

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

Conclusion & Outlook

- Interplay of strong and weak interaction
- Unique probe of nonperturbative strong interactions
- High-intensity sources
  - Low energies
  - Few-nucleon systems
- EFT ideally suited
- 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

MRS, R. P. Springer, Prog. Part. Nucl. Phys. **72**, 1 (2013)

Wasem (2012)

Parity violation in pionful EFT

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

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

- h_π: PV πN isovector coupling
- PV in Compton scattering and pion production on the nucleon
- Pion-exchange contributions to NN potential

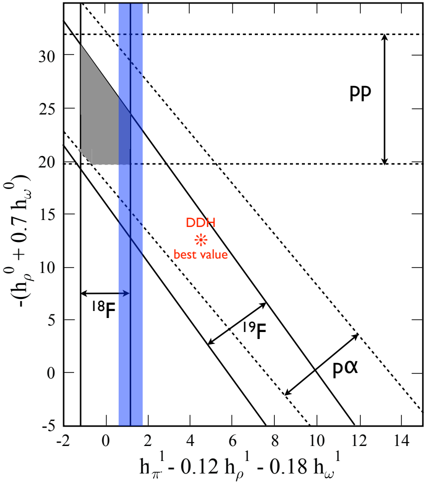
Kaplan, Savage (1993); Chen, Ji (2001); Zhu et al. (2001)

PV *NN* potential

- $\mathcal{O}(Q^{-1})$:
  - one-pion exchange $\propto h_\pi$
  - LO contribution to $\vec{n}p \to d\gamma$
- $\mathcal{O}(Q^{1})$:
  - Contact terms analogous to EFT($\not{\pi}$)
  - TPE $\propto h_\pi$
  - New $\gamma\pi NN$ contact interaction
- Employed in
  - $\vec{N}N$, $np \leftrightarrow d\gamma$, anapole moments
  - Beyond two-nucleon sector: hybrid calculation for *nd* scattering and $\vec{n}d \to t\gamma$

Savage, Springer (1998); Kaplan et al. (1999); Zhu et al. (2005); Liu (2007); Song et al. (2011), (2012)

Extractions from experiments



Haxton, Holstein (2013)