Hadronic parity violation in few-nucleon systems

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The theory of parity violation in few-nucleon systems

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\textbf{ABSTRACT}

We review recent progress in the theoretical description of hadronic parity violation in few-nucleon systems. After introducing the different methods that have been used to study parity-violating observables we discuss the available calculations for reactions with up to five nucleons. Particular emphasis is put on effective field theory calculations where they exist, but earlier and complementary approaches are also presented. We hope this review will serve as a guide for those who wish to know what calculations are available and what further calculations need to be completed before we can claim to have a comprehensive picture of parity violation in few nucleon systems.

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Introduction and motivation

Parity-violating NN interactions

Two-nucleon systems

Three-nucleon systems

Few-nucleon systems

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
Motivation

- Weak neutral current in hadron sector
- Probe of strong interactions
  - Weak interactions short-ranged
  - Sensitive to quark-quark correlations inside nucleon
  - No need for high-energy probe
  - “Inside-out probe”
- Isospin dependence of interaction strengths?
  \[ \Delta I = 1/2 \] puzzle (strangeness-changing )?
Observables

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

Complex nuclei
- Enhancement up to 10% effect ($^{139}\text{La}$)
- Theoretically difficult
Two-nucleon system
- $\vec{pp}$ scattering (Bonn, PSI, TRIUMF, LANL)
- $\vec{np} \rightarrow d\gamma$ (SNS, LANSCE, Grenoble)
- $d\gamma \leftrightarrow np?$ (HIGS2?)
- $\vec{np}$ 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)
- $\vec{nd} \rightarrow t\gamma$ (SNS?)
- $\vec{\gamma}^3\text{He} \rightarrow pd$?
- $\vec{nd}$ spin rotation?
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) ⇒ ranges and “best values”

- Combined with variety of PC potentials

- Extensions to include two-pion exchange, $\Delta, \ldots$

- 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
Pionless EFT

Structure of interactions
- At very low energies: pion exchange not resolved
- Only nucleons as explicit degrees of freedom
- Contact terms with increasing number of derivatives

Applications in $A = 2 - 6$
- Two nucleons
  - $np \rightarrow d\gamma$
  - Deuteron properties
  - . . .

Chen et al. (1999); Rupak (2000)
Three nucleons

- *nd* scattering
- \( nd \rightarrow t\gamma \)
- \(^3\)H and \(^3\)He binding energies
- \(^3\)H charge radius
- ...

Four+ nucleons

- Ground, 1st excited state of \(^4\)He
- \( n^3\)H, \( n^3\)He, \( p^3\)He scattering lengths
- \(^3\)H – a(\( n^3\)He) correlation
- \(^6\)Li ground state

Platter et al. (2004,05,07); Stetcu et al. (2006,09); Kirscher et al. (2010,13)
Parity violation in EFT($\mathcal{A}$)

Structure of interaction

- Only nucleons
- Contact interactions
- 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

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Lowest-order parity-violating Lagrangian

Partial wave basis

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

- Need 5 experimental results to determine LECs

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

Neutron-proton spin rotation

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

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

- Estimate

\[
\left. \frac{d\phi_{np}^{PV}}{dL} \right| \approx [10^{-7} \ldots 10^{-6}] \frac{\text{rad}}{\text{m}}
\]

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Grießhammer, MRS, Springer (2012)
Electromagnetic processes: $np \leftrightarrow d\gamma$

Invariant amplitude for $np \rightarrow d\gamma$

\[ M = eX N^T \tau_2 \sigma_2 \left[ \sigma \cdot q \, \epsilon_d^* \cdot \epsilon_\gamma^* - \sigma \cdot \epsilon_\gamma^* \, q \cdot \epsilon_d^* \right] N + i e Y \epsilon^{ijk} \epsilon_d^* \epsilon_{\gamma}^* \epsilon_i q_j \epsilon_{\gamma}^* k \left( N^T \tau_2 \tau_3 \sigma_2 N \right) + i e W \epsilon^{ijk} \epsilon_d^* \epsilon_i \epsilon_{\gamma}^* k \left( N^T \tau_2 \sigma_2 \sigma_i N \right) + e V \epsilon_d^* \cdot \epsilon_{\gamma}^* \left( N^T \tau_2 \tau_3 \sigma_2 N \right) + \ldots \]

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

Kaplan et al. (1999)
Polarized capture: $\vec{n}p \rightarrow d\gamma$

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

- Quantity of interest

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

- \[
A_\gamma = -2 \frac{M}{\gamma^2} \frac{\text{Re}[Y^* W]}{|Y|^2} = \frac{4}{3} \sqrt{2} \frac{M_2^3}{\pi \kappa_1} \left(1 - \gamma a_1^{S_0}\right) \ g^{(3S_1 - 3P_1)}
\]

- Experiment: Currently consistent with zero

- NPDGamma @ SNS: $A_\gamma$ to $10^{-8}$

Savage (2001); MRS, Springer (2009)
Induced circular polarization: \( np \rightarrow d\vec{\gamma} \)

Circular polarization

- Quantity of interest

\[
P_\gamma = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
\]

\[
P_\gamma = 2 \frac{M \text{ Re}[Y^* V]}{\gamma^2 \left| Y \right|^2}
\]

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

- Information complementary to \( \vec{n}p \rightarrow d\gamma \)
- 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: $P_\gamma = A_\gamma^L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
- Flagship experiment at possible HI\(\gamma\)S intensity upgrade
- Model calculation:
  - AV18+DDH or CD-Bonn+DDH
  - Two different PV parameter sets
  - At $\omega = 2.2259$ MeV

<table>
<thead>
<tr>
<th>Bonn+DDH-adj</th>
<th>AV18+DDH-adj</th>
<th>AV18+DDH</th>
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<td>$9.05 \times 10^{-8}$</td>
<td>$5.19 \times 10^{-8}$</td>
<td>$2.38 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

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

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

![Graph showing $a_3$ 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

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No PV three-body operator at LO and NLO

- Verified numerically

Grießhammer, MRS (2010)
PV $\bar{n}d$ scattering

- $\bar{n}d$ forward scattering with one PV insertion
- At LO: tree-level, “one-loop,” “two-loop” diagrams:
Neutron-deuteron spin rotation at NLO

- Spin-rotation angle at NLO

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

- Estimate

\[
\left| \frac{d\phi_{PV}^{nd}}{dL} \right| \approx \left[ 10^{-7} \ldots 10^{-6} \right] \text{ rad m}^{-1}
\]

Grießhammer, MRS, Springer (2012)
Few-body systems

$\bar{n}^3\text{He} \rightarrow p^3\text{H} \ (\vec{\sigma}_n \cdot \vec{p}_p)$

- Parity-conserving: AV18+UIX/N$^3$LO+N$^2$LO
- Parity-violating: DDH/EFT($\not{n}$)
- DDH: dependence on PC potential
- EFT($\not{n}$): dependence on PC potential + scale dependence
- Planned at SNS $\rightarrow$ 2014

$\bar{N}\alpha$ scattering ($\vec{\sigma}_p \cdot \vec{p}_p$)

- DDH + simple models
- No calculation in terms of NN interactions
- $\vec{p}\alpha$ scattering measured at 46 MeV (PSI)
- $\vec{n}\alpha$ spin rotation measured at NIST ($\rightarrow$ improve statistics)

Viviani et al. (2010); Roser, Simonius (1985); Flambaum et al. (1985); Dmitriev et al. (1983); Lang et al. (1985); Snow et al. (2011)
Light nuclei

Possible to measure PV in
- $^6\text{Li}(n, \alpha)^3\text{H}$
- $^{10}\text{B}(n, \alpha)^7\text{Li}$
- $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow ^7\text{Li} + \gamma$

No *ab initio* calculations

Vesna et al. (2000), (2008)
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 $\pi N$ couplings
- Lattice QCD: preliminary result for PV $\pi N$ coupling $h_\pi$

Wasem (2012)
Parity violation in pionful EFT

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

$$\mathcal{L}^{PV} = \frac{h_\pi F}{2\sqrt{2}} \bar{N}X_3 N + \ldots$$

$$= ih_\pi (\pi^+ \bar{p}n - \pi^- \bar{n}p) + \ldots$$

- $h_\pi$: PV $\pi N$ isovector coupling
- PV in Compton scattering and pion production on the nucleon
- Pion-exchange contributions to $NN$ potential

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

- $\mathcal{O}(Q^1)$:
  - Contact terms analogous to EFT($\not\pi$)
  - TPE $\propto h_\pi$
  - New $\gamma\pi NN$ contact interaction

Employed in
- $\vec{NN}$, $np \leftrightarrow d\gamma$, anapole moments
- Beyond two-nucleon sector: hybrid calculation for $nd$ scattering and $\vec{n}d \rightarrow t\gamma$

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

Multipole expansion of charge and current operators

- P and T conserving: charge, electric quadrupole, magnetic dipole, . . .
- P and T violating: electric dipole, magnetic quadrupole, . . .
- P violating, T conserving: anapole moment, . . .

Current matrix element

\[
\langle N(p') | J^\mu | N(p) \rangle = \bar{u}(p') \left[ \gamma^\mu F_1(q^2) + i \frac{\sigma^{\mu\nu} q_\nu}{2m} F_2(q^2) \\
+ \frac{1}{m^2} (q q^\mu - q^2 \gamma^\mu) \gamma_5 a(q^2) \\
+ i \frac{\sigma^{\mu\nu} q_\nu}{2m} \gamma_5 d(q^2) \right] u(p)
\]

Zel’dovich (1958); Flambaum et al. (1980); Haxton et al. (2002)
Anapole moment

- Spin-dependent
- Contributes to hyperfine dependence of atomic PV
- Enhanced in heavy nuclei as $A^{2/3}$
- Shell-model calculations
Extractions from experiments

Haxton, Holstein (2013)