Hadronic parity violation in few-nucleon systems

Matthias R. Schindler

University of South Carolina

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Review

The theory of parity violation in few-nucleon systems

M.R. Schindler [a,*], R.P. Springer [b]

[a] *Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA*
[b] *Department of Physics, Duke University, Durham, NC, USA*

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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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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

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?
  $\rightarrow \Delta I = 1/2$ puzzle (strangeness-changing)?

Observables

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

- Interference between PC and PV amplitudes
- Longitudinal asymmetries
- Angular asymmetries
- γ circular polarization
- Spin rotation
- Anapole moment

Complex nuclei

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

Two-nucleon system

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

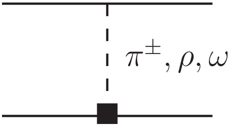
Few-nucleon systems

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

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
  - $np \to d\gamma$
  - Deuteron properties
  - ...

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

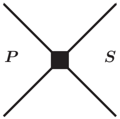
- Three nucleons
  - *nd* scattering
  - $nd \to t\gamma$
  - ^{3}H and ^{3}He binding energies
  - ^{3}H charge radius
  - …
- Four+ nucleons
  - Ground, 1st excited state of ^{4}He
  - $n\,^3$H, $n\,^3$He, $p\,^3$He scattering lengths
  - ^{3}H – a(n ^{3}He) correlation
  - ^{6}Li ground state

Platter et al. (2004,05,07); Stetcu et al. (2006,09); Kirscher et al. (2010,13)

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

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

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

- Need 5 experimental results to determine LECs

Phillips, MRS, Springer (2009)

PV nucleon-nucleon scattering

- Polarized beam on unpolarized target

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

- 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

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

- 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)

Electromagnetic processes: $np \leftrightarrow d\gamma$

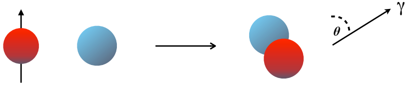
Invariant amplitude for $np \to d\gamma$

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

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

Kaplan et al. (1999)

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



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

- Quantity of interest

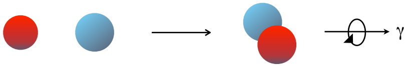
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$$

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

- 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

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

-

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

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

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

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

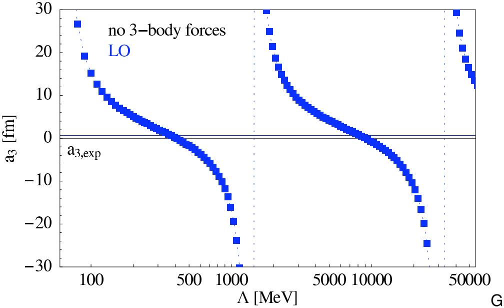
- For reversed kinematics: $P_\gamma = A_L^\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
- Flagship experiment at possible HIγS intensity upgrade
- Model calculation:
  - AV18+DDH or CD-Bonn+DDH
  - Two different PV parameter sets
  - At $\omega = 2.2259\,\text{MeV}$

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



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

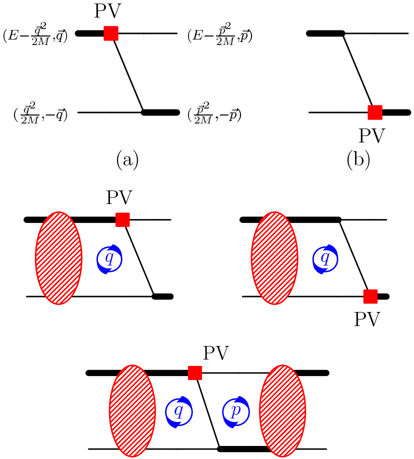
No PV three-body operator at LO and NLO

- 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)

Few-body systems

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

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

$\vec{N}\,\alpha$ 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 ($\to$ 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}Li(n, α)^{3}H
  - ^{10}B(n, α)^{7}Li
  - ^{10}B(n, α)^{7}Li$^* \rightarrow {}^7$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 πN couplings
- Lattice QCD: preliminary result for PV πN coupling h_π

Wasem (2012)

Parity violation in pionful EFT

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

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

- 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)

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

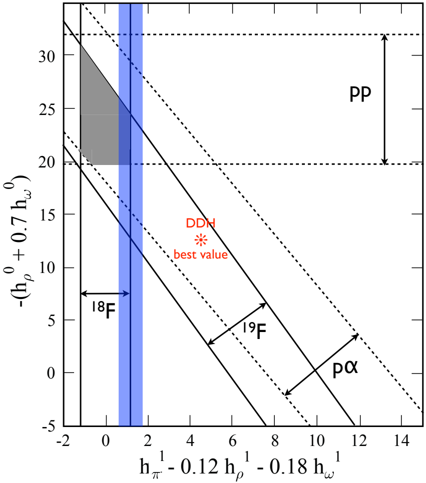
$$
\begin{aligned}
\langle N(p')|J^\mu|N(p)\rangle = \bar{u}(p')\Big[&\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m} F_2(q^2) \\
&+ \frac{1}{m^2}(\not{q}q^\mu - q^2\gamma^\mu)\gamma_5\, a(q^2) \\
&+ i\frac{\sigma^{\mu\nu}q_\nu}{2m}\gamma_5\, d(q^2)\Big] u(p)
\end{aligned}
$$

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 $A^{\frac{2}{3}}$
- Shell-model calculations

Extractions from experiments



Haxton, Holstein (2013)