Hadronic parity violation in few-nucleon systems

Matthias R. Schindler

UNIVERSITY OF SOUTH CAROLINA

Nuclei and Fundamental Symmetries:
Theory Needs of Next-Decade Experiments
August 9, 2013

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

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)
- $\vec{n}p \rightarrow d\gamma$ (SNS, LANSCE, Grenoble)
- $d\vec{\gamma} \leftrightarrow np$? (HIGS2?)
- $\vec{n}p$ spin rotation?

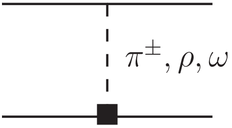
Few-nucleon systems

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

PV potential

DDH model

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



- Weak interaction encoded in PV meson-nucleon couplings
- Estimate 6 (7) weak couplings (quark models, symmetries) $\Rightarrow$ ranges and "best values/guesses"
- Combined with variety of PC potentials
- Extensions to include two-pion exchange, Δ,...

Desplanques, Donoghue, Holstein (1980)

Experimental prospects

Ongoing and planned experiments

- High-intensity neutron & photon sources
- Cold neutrons
- Few-nucleon systems

EFT($\not\pi$)

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

Pionless EFT

Applications in $A = 2 - 6$

- Two nucleons
  - $np \to d\gamma$
  - ...
- Three nucleons
  - nd scattering
  - $nd \to t\gamma$
  - ^{3}H and ^{3}He binding energies
  - ^{3}H charge radius
  - ...

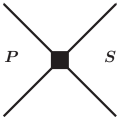
Chen et al. (1999); Rupak (2000); Platter et al. (2004,05,07); Kirscher et al. (2010,13)

- 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

Stetcu et al. (2006,09); Kirscher et al. (2010,13)

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

- Nucleon contact terms
- 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); Zhu et al. (2005); 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)

$\vec{N}N$ in EFT($\not\pi$)

- 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)

$\vec{n}p$ spin rotation

- Transmission of perpendicularly polarized beam

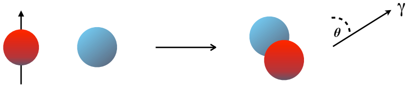
$$\frac{1}{\rho}\,\frac{d\phi^{np}_{\rm PV}}{dL}\bigg|_{\rm LO+NLO} = \Big\{[9.0\pm 0.9]\,\Big(2g^{(^3S_1-^3P_1)}+g^{(^3S_1-^1P_1)}\Big)$$

$$-\,[37.0\pm 3.7]\,\Big(g^{(^1S_0-^3P_0)}_{(\Delta I=0)}-2g^{(^1S_0-^3P_0)}_{(\Delta I=2)}\Big)\Big\}\text{rad MeV}^{-\frac{1}{2}}$$

- Estimate

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

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



- Polarized neutron capture

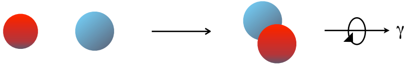
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$$

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

- NPDGamma @ SNS
- Related to deuteron anapole moment through $\mathcal{C}^{(^3S_1-{}^3P_1)}$

Savage (2001); MRS, Springer (2009)

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



- Circular polarization

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

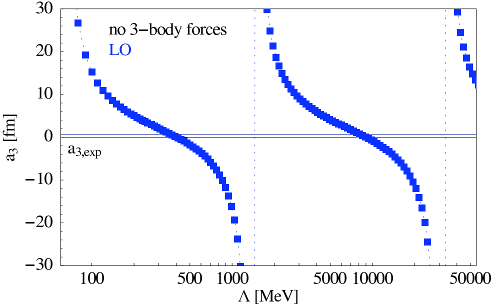
- Information complementary to $\vec{n}p \to d\gamma$
- Experimental result $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$
- Related to A_L^γ in $\vec{\gamma}d \to np$:

Measure at upgraded HIGS facility?

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

Three-nucleon interaction

- Two-body information insufficient to determine PV LECs
- Require PV three- and few-body observables
- *nd* scattering in $^2S_{\frac{1}{2}}$ channel: scattering length a_3 vs cutoff

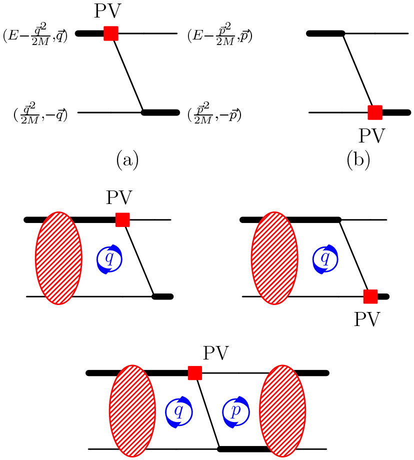


- Three-body counterterm at leading order
- PV three-body operators? Additional experimental input?

Danilov (1961); Bedaque, Hammer, van Kolck (2000)

PV $\vec{n}d$ scattering

- $\vec{n}d$ scattering with one PV insertion
- Tree-level, “one-loop,” “two-loop” diagrams:



Grießhammer, MRS, Springer (2011); Vanasse (2011)

PV three-nucleon interactions

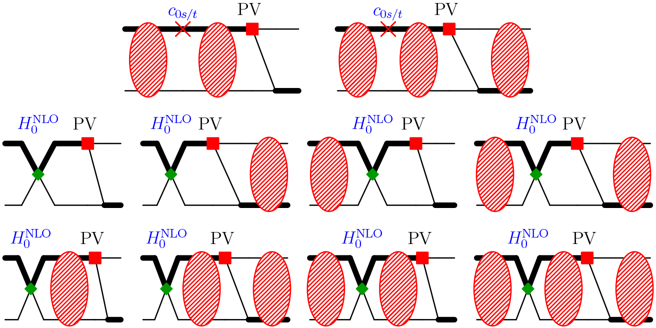
Analyze PV $\vec{n}d$ scattering

- Leading order
  - Asymptotic PC amplitude $\Rightarrow$ possible divergence
  - Angular integration vanishes
  - No PV 3N interaction at LO
- Next-to-leading order
  - Analyze spin-isospin structure of possible divergences
  - Do not match possible NLO 3N operator structures
  - No PV 3N interaction at NLO
- Verified numerically

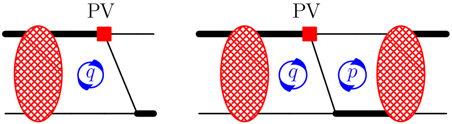
Grießhammer, MRS (2010)

PV $\vec{n}d$ scattering at NLO

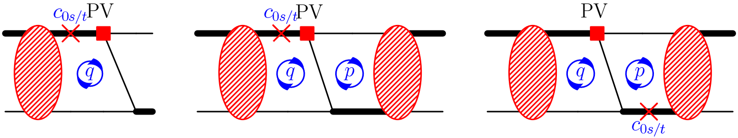
- NLO diagrams: “Class I”



- Reformulation in “partially resummed” formalism



- NLO diagrams: “Class II”



Neutron-deuteron spin rotation at NLO

- Spin-rotation angle

$$\frac{1}{\rho}\,\frac{d\phi^{nd}_{\mathrm{PV}}}{dL} = \Big([16.0 \pm 1.6]\, g^{(^3S_1-^1P_1)} \;-\; [36.6 \pm 3.7]\;\; g^{(^3S_1-^3P_1)}$$
$$+\;[4.6 \pm 1.0]\;\Big(3g^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2g^{(^1S_0-^3P_0)}_{(\Delta I=1)}\Big)\Big)\mathrm{rad\ MeV}^{-\frac{1}{2}}$$

- Estimate

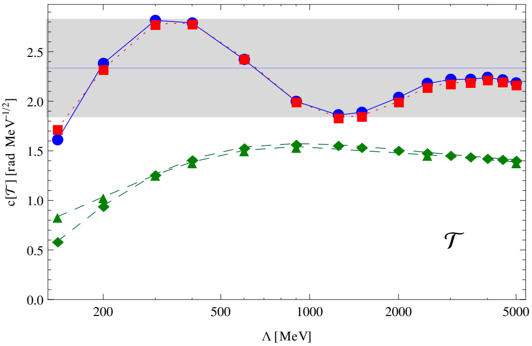
$$\left|\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L}\right| \approx \left[10^{-7}\cdots 10^{-6}\right]\;\frac{\mathrm{rad}}{\mathrm{m}}$$

Grießhammer, MRS, Springer (2011)

Error estimate

Determine theoretical error

- $N^2LO \sim Q^2 \approx 0.1$
- Cutoff dependence of coefficients of
  $\mathcal{T} = 3g^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2g^{(^1S_0-^3P_0)}_{(\Delta I=1)}$



- Maps out higher-order contributions

Hybrid calculations: *nd* spin rotation

Hybrid

- AV18+UIX
- PV potential derived from EFT($\not\pi$)
- Regulator $\frac{\mu_P^2}{4\pi r} e^{-\mu_P r}$
- Suggested value: $\mu_P = 138\,\text{MeV}$
- $\frac{1}{\rho}\frac{d\phi}{dl} = \sum c_n I_n$
- PV couplings c_n taken scale-independent

Consistent EFT($\not\pi$) calculation

- Observable scale-independent
- Scale-dependent couplings
- Translate in couplings c_n

Schiavilla et al. (2008), Grießhammer, MRS, Springer (2012)

Translated values for I_n ($[\mu_p, \mu] =$ MeV)

	Hybrid	Translated				
n	$\mu_P = 138$	$\mu = 100$	$\mu = 125$	$\mu = 138$	$\mu = 170$	$\mu = 200$
1	63.2	85.0	118.4	136	178	219
4	57.8	42.4	52.2	57.3	69.8	81.5
8	-75.2	-53.2	-68.9	-77.1	-97.3	-116
9	-6.11	-10.4	-9.33	-8.77	-7.40	-6.12

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

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

- DDH + simple model
- No calculation in terms of NN interactions
- Measured at 46 MeV (PSI)

Viviani et al. (2010); Roser, Simonius (1985); Flambaum et al. (1985)

$\vec{n}\,{}^4$He spin rotation

- DDH + simple model
- No calculation in terms of NN interactions
- DDH preferred ranges

$$-1.6 \times 10^{-6}\,\frac{\text{rad}}{\text{m}} < \frac{d\phi}{dl} < 1.2 \times 10^{-6}\,\frac{\text{rad}}{\text{m}}$$

- Measured at NIST

$$\frac{d\phi}{dl} = [+1.7 \pm 9.1\,(\text{stat.}) \pm 1.4\,(\text{sys.})] \times 10^{-7}\,\frac{\text{rad}}{\text{m}}$$

- Plans to improve statistics

Dmitriev et al. (1983)

Light nuclei

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

Wasem (2012)