Violating symmetries: parity non-conservation in nucleon interactions

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Nucleon interactions

- Manifestation of interactions between nucleon constituents
- Bulk of interactions from strong interactions (QCD)
- QCD conserves parity
- Quarks interact weakly
- Parity violation in weak interactions

  $\Rightarrow$ Parity-violating component in nucleon interaction

- Relative strength $\sim G_F m_\pi^2 \approx 10^{-7}$

Hadronic weak interactions

- At low energies for $\Delta S = 0$

$$\mathcal{L}_{weak}^{\Delta S=0} = \frac{G}{\sqrt{2}} \left[\underbrace{\cos^2\theta_C J_W^{0,\dagger} J_W^0}_{\Delta I=0,2} + \underbrace{\sin^2\theta_C J_W^{1,\dagger} J_W^1}_{\Delta I=1} + J_Z^\dagger J_Z \right]$$

- $\Delta I = 1$ dominated by neutral current J_Z ($\sin^2\theta_C \sim 0.05$)
- Neutral currents cannot be observed in flavor changing hadronic decays

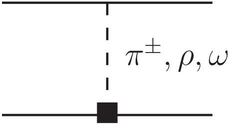
Weak interaction

- Well-understood between quarks
- Mediated by W, Z exchange
- Range $\sim$ 0.002 fm
- How manifested for quarks bound in nucleon?
- Sensitivity to quark-quark correlations in nucleon
- “Inside-out” probe
- Isolate through parity-violation

Parity violation model

Desplanques, Donoghue, Holstein

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

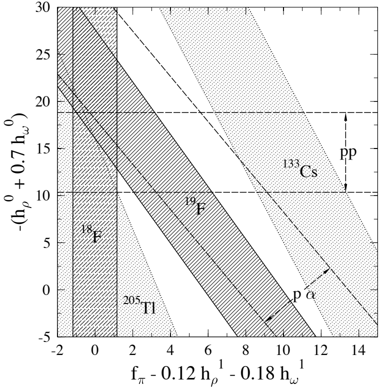


- Estimate weak couplings (quark models, symmetries) $\Rightarrow$ ranges and "best values"
- Has been standard for analyzing experiments

Desplanques, Donoghue, Holstein (1980)

DDH model

- Potential problems
  - Isovector coupling from ^{18}F small compared to DDH value
  - Isoscalar coupling from ^{133}Cs differs from other results

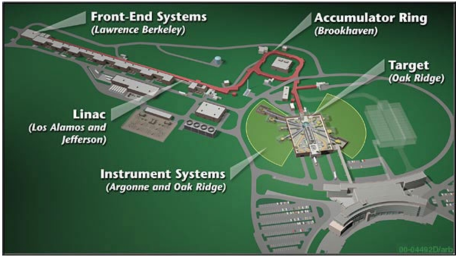


Haxton (2008)

- Possible explanation: model assumptions not valid?
  - Restriction on spectrum
  - No two-pion-exchange
  - . . .

Few-nucleon experiments

- Complex nuclei: enhancement up to $\sim$ 10% effect
  - Relation to *NN* interaction?
  - Theoretically difficult
- Two-nucleon system
  - $\vec{p}p$ scattering (Bonn, PSI, TRIUMF, LANL)
  - $\vec{n}p \to d\gamma$ (SNS, LANSCE, Grenoble)
  - $\vec{n}p$ 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)
  - $\vec{n}d \to t\gamma$ (SNS?)
  - $\vec{n}d$ spin rotation?



Theory goals

Variety of experiments

- Unified framework
- Model-independent
- Check consistency of results
- Defendable theoretical errors

Two- and few-body systems

- Energies $\lesssim$ 10s of MeV
- Ideally suited for EFT($\not\pi$)

Effective field theories for PV

One-nucleon sector

- PV πN coupling

Two-nucleon sector

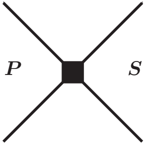
- Pionless theory: *NN* contact interactions
- Explicit pions: *NN* contact interactions and PV πN coupling
- "Hybrid" approach: EFT PV potential combined with phenomenological wave functions
  $\rightarrow$ resolution mismatch?

Kaplan, Savage (1993); Savage, Springer (1998); Savage (2001); Zhu, Maekawa, Holstein, Ramsey-Musolf, van Kolck (2005); Liu (2007)

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



- Spin, isospin: 5 different combinations
- No new constants for electromagnetic effects $\rightarrow$ gauging

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

Lowest-order parity-violating Lagrangian

Partial wave basis

$$\mathcal{L}_{PV} = -\Big[\mathcal{C}^{(^3S_1-^1P_1)}\left(N^T\sigma_2\,\vec{\sigma}\tau_2 N\right)^\dagger\cdot\left(N^T\sigma_2\tau_2 i\overleftrightarrow{\nabla}N\right)$$

$$+\,\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\left(N^T\sigma_2\tau_2\vec{\tau}N\right)^\dagger\left(N^T\sigma_2\,\vec{\sigma}\cdot i\overleftrightarrow{\nabla}\,\tau_2\vec{\tau}N\right)$$

$$+\,\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\,\epsilon^{3ab}\left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger\left(N^T\sigma_2\,\vec{\sigma}\cdot\overleftrightarrow{\nabla}\,\tau_2\tau^b N\right)$$

$$+\,\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\,\mathcal{I}^{ab}\left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger\left(N^T\sigma_2\,\vec{\sigma}\cdot i\overleftrightarrow{\nabla}\,\tau_2\tau^b N\right)$$

$$+\,\mathcal{C}^{(^3S_1-^3P_1)}\,\epsilon^{ijk}\left(N^T\sigma_2\sigma^i\tau_2 N\right)^\dagger\left(N^T\sigma_2\sigma^k\tau_2\tau_3\overleftrightarrow{\nabla}^j N\right)\Big]$$

$$+\,h.c.$$

Phillips, MRS, Springer (2009)

Dibaryon formalism

$$\begin{aligned}\mathcal{L}^{d}_{PV} = - \Big[& g^{(^3S_1-^1P_1)} t_i^\dagger \left(N^T \sigma_2 \tau_2 i \overleftrightarrow{\nabla}_i N \right) \\ & + g^{(^1S_0-^3P_0)}_{(\Delta I=0)} s_a^\dagger \left(N^T \tau_2 \tau_a \sigma_2 \, \vec{\sigma} \cdot i \overleftrightarrow{\nabla} N \right) \\ & + g^{(^1S_0-^3P_0)}_{(\Delta I=1)} \, \epsilon^{3ab} s_a^\dagger \left(N^T \tau_2 \tau^b \sigma_2 \, \vec{\sigma} \cdot \overleftrightarrow{\nabla} N \right) \\ & + g^{(^1S_0-^3P_0)}_{(\Delta I=2)} \, \mathcal{I}^{ab} s_a^\dagger \left(N^T \tau_2 \tau^b \sigma_2 \, \vec{\sigma} \cdot i \overleftrightarrow{\nabla} N \right) \\ & + g^{(^3S_1-^3P_1)} \, \epsilon^{ijk} t_i^\dagger \left(N^T \tau_2 \tau_3 \sigma_2 \sigma^k \overleftrightarrow{\nabla}^j N \right) \Big] + h.c.\end{aligned}$$

Relation between couplings

$$g^{X-Y} = \sqrt{\frac{\pi}{r^X} \frac{8}{M}} \frac{C^{X-Y}}{C_0^X}$$

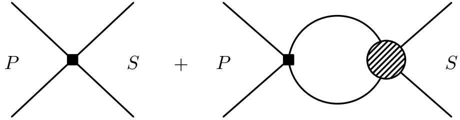
MRS, Springer (2009)

Nucleon-nucleon scattering

- Simplest process
- Parity-violating contribution suppressed by $\sim 10^{-7}$
- $\vec{N}N$ cross section
  - Strong contribution does not depend on helicity
  - Weak contribution does depend on helicity
- Consider asymmetry in $\vec{N} + N$

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

- Interference between strong and weak



Leading-order results: *pp*/*nn*

$$A_L^{pp/nn} = 8p\frac{\mathcal{A}_{pp/nn}}{\mathcal{C}_0^{^1S_0}}$$

$$\mathcal{A}_{pp} = 4\left(\mathcal{C}_{(\Delta I=0)}^{(^1S_0-^3P_0)} + \mathcal{C}_{(\Delta I=1)}^{(^1S_0-^3P_0)} + \mathcal{C}_{(\Delta I=2)}^{(^1S_0-^3P_0)}\right)$$
$$\mathcal{A}_{nn} = 4\left(\mathcal{C}_{(\Delta I=0)}^{(^1S_0-^3P_0)} - \mathcal{C}_{(\Delta I=1)}^{(^1S_0-^3P_0)} + \mathcal{C}_{(\Delta I=2)}^{(^1S_0-^3P_0)}\right)$$

- No Coulomb interaction for *pp*
- Depends on ratio of PV and PC constant

$\Rightarrow$ Renormalization point-dependence of $\mathcal{A}_{pp/nn}$ dictated by $\mathcal{C}_0^{^1S_0}$

Leading-order results: *np*

$$A_L^{np} = 8p\left(\frac{\frac{d\sigma^{^1S_0}}{d\Omega}}{\frac{d\sigma^{^1S_0}}{d\Omega}+3\frac{d\sigma^{^3S_1}}{d\Omega}}\frac{\mathcal{A}_{np}^{^1S_0}}{\mathcal{C}_0^{^1S_0}}+\frac{\frac{d\sigma^{^3S_1}}{d\Omega}}{\frac{d\sigma^{^1S_0}}{d\Omega}+3\frac{d\sigma^{^3S_1}}{d\Omega}}\frac{\mathcal{A}_{np}^{^3S_1}}{\mathcal{C}_0^{^3S_1}}\right)$$

$$\mathcal{A}_{np}^{^1S_0} = 4\left(\mathcal{C}_{(\Delta I=0)}^{(^1S_0-^3P_0)} - 2\mathcal{C}_{(\Delta I=2)}^{(^1S_0-^3P_0)}\right)$$

$$\mathcal{A}_{np}^{^3S_1} = 4\left(\mathcal{C}^{(^3S_1-^1P_1)} - 2\mathcal{C}^{(^3S_1-^3P_1)}\right)$$

$$\frac{d\sigma}{d\Omega} = \left[\left(\frac{1}{a}\right)^2 + p^2\right]^{-1}$$

- Measure at 2 different energies: disentangle $\mathcal{A}_{np}^{^1S_0}$ and $\mathcal{A}_{np}^{^3S_1}$

Coulomb corrections

- Coulomb corrections can be included in EFT($\not\pi$)
- Coulomb parameter $\eta = \frac{M\alpha}{2p}$
- Integrals for cross section over finite range $\theta_1 \leq \theta \leq \theta_2$
- For $T_{\rm lab} = 0.1$ MeV: $\eta \approx 0.26 \Rightarrow$ expand in η

$$A_L^{pp} = 8p\frac{\mathcal{A}_{pp}}{\mathcal{C}_0^{^1S_0}}\left[1 + \eta\left(\frac{1}{a_S(\mu)p}\right)\frac{1}{\cos\theta_1 - \cos\theta_2}\ln\left(\frac{1-\cos\theta_1}{1-\cos\theta_2}\right)\right.$$
$$\left. + \mathcal{O}(\eta)^2\right]$$

Kong and Ravndal (1999)

Comparison with experiment

- *pp* scattering experiments ($23^o < \theta_{lab} < 52^o$)

$$A_L^{\vec{p}p}(E = 13.6\text{ MeV}) = (-0.93 \pm 0.21) \times 10^{-7}$$
$$A_L^{\vec{p}p}(E = 45\text{ MeV}) = (-1.50 \pm 0.22) \times 10^{-7}$$

- From result at $E = 13.6$ MeV:

$$\frac{\mathcal{A}_{pp}}{\mathcal{C}_0^{^1S_0}} = (-1.5 \pm 0.3) \times 10^{-10}\text{ MeV}^{-1}$$

- Coulomb correction ~ 3 percent
- Use to 'predict' asymmetry at 45 MeV

$$A_L^{\vec{p}p}(E = 45\text{ MeV}) = (-1.69 \pm 0.38) \times 10^{-7}$$

- In agreement with experiment

Eversheim (1991); Kistryn (1987)

Higher-order corrections

- At $E = 45$ MeV center-of-mass momentum $p > m_\pi$
- Resum higher-order corrections in PC sector
- Re-analyze low-energy *pp* measurement (no Coulomb)

$$\frac{\mathcal{A}_{pp}(\mu = m_\pi)}{\mathcal{C}_0^{^1S_0}} = (-1.1 \pm 0.25) \times 10^{-10}\ \text{MeV}^{-1}$$

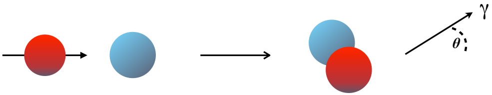
$\sim$ 30% difference

- "Prediction" for $E = 45$ MeV

$$A_L^{\vec{p}p}(E = 45\text{MeV}) = (-2.6 \pm 0.6) \times 10^{-7}$$

Compare to -1.69×10^{-7}: $>$ 50% difference

Electromagnetic processes: $\vec{n}p \to d\gamma$



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

- Quantity of interest

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

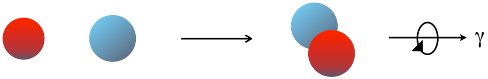
-

$$A_\gamma = \frac{32}{3}\frac{M}{\kappa_1(1-\gamma a^{^1S_0})}\frac{\mathcal{C}^{(^3S_1-^3P_1)}}{\mathcal{C}_0^{^3S_1}}$$

- Experiment: Currently consistent with zero
- NPDGamma @ SNS: A_γ to 10^{-8}
- Related to deuteron anapole moment through $\mathcal{C}^{(^3S_1-^3P_1)}$

Savage (2001); MRS, Springer (2009)

Electromagnetic processes: $np \to d\vec{\gamma}$



Circular polarization

- Quantity of interest

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

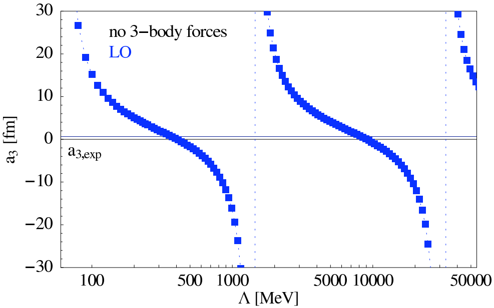
- $$P_\gamma \sim a\frac{\mathcal{C}^{(^3S_1-^1P_1)}}{\mathcal{C}_0^{^3S_1}} + b\frac{\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}}{\mathcal{C}_0^{^1S_0}}$$

- Experimental result consistent with $P_\gamma = 0$
- Use high-intensity free electron lasers for $\vec{\gamma}d \to np$?

MRS, Springer (2009); Knyazkov (1983)

Three-body observables

- Two-body information not sufficient to determine PV LECs
- Require three- and few-body observables
- PV three-body operators?
- Parity-conserving sector:
  - Naive dimensional analysis: three-body terms higher-order
  - *nd* scattering in ${}^2S_{\frac{1}{2}}$ channel
  - Three-body counterterm at leading order



Efimov (1974); Bedaque, Hammer, van Kolck (2000)

PV three-body operators

General structure at LO

- $S - P$ transitions
- Conserve J

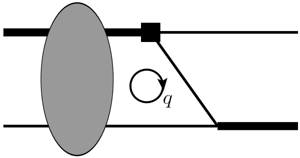
$$^2S_{\frac{1}{2}} - {}^2P_{\frac{1}{2}}, {}^2S_{\frac{1}{2}} - {}^4P_{\frac{1}{2}}$$

- Include isospin

4 LO PV 3-body operators

PV three-body operators at LO

- Possible divergence from ${}^2S_{\frac{1}{2}}$ part in PC amplitude in



- Asymptotic behavior

$$t_{PV,l}^{\text{1-loop}} \sim \int \frac{dq}{q^{2+s_l(\lambda)}} \int d\Omega_q Y_{lm}(\Omega_q)\, \vec{q} \cdot \epsilon \vec{K}_{PV} \sum_{n=0}^{\infty} c_n \left(\frac{\vec{p} \cdot \vec{q}}{q^2} \right)^n$$

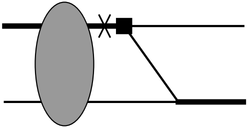
- $s_0(1) = 1.00624\ldots i, n = 0$ leads to logarithmic divergence
- Angular integral vanishes for $n = 0$

No PV three-body operator at leading order

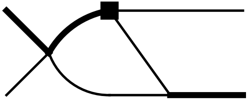
Grießhammer, Phillips, MRS

PV three-body operators at NLO

- NLO correction to PC sector leads to divergence



- Cannot be absorbed by PV $S - P$ 3-body counterterm
- Contribution from PC 3-body counterterm at same order



No PV three-body operator at NLO (?)

Grießhammer, MRS

Conclusion & Outlook

Hadronic parity violation

- Gate to neutral current weak interaction
- Probe non-perturbative QCD phenomena: inside-out probe
- Current and proposed experiments
  - Low-energy
  - Few-nucleons
- Need consistent analysis and interpretation

Conclusion & Outlook

EFT for parity-violating *NN* interactions

- 5 independent operators at LO in EFT($\not\pi$)
- 2-body observables
  - $\vec{p}p$ scattering
  - $\vec{n}p$ spin rotation
  - $np \leftrightarrow d\gamma$
  - Not enough information
- PV 3 body sector
  - No PV 3-body operators at LO and NLO
  - $\vec{n}d$ spin rotation
  - $\vec{n}d \rightarrow t\gamma$
- Few-body observables
- Lattice