Hadronic parity violation in effective field theories

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Bound states and resonances in effective field theories and lattice QCD calculations

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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
- Interplay of weak and nonperturbative strong interactions

Weak quark-quark interactions

- Well-tested in leptonic and semi-leptonic processes
- For strangeness-conserving hadronic sector at low energies

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

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

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?

Experimental prospects

Ongoing and planned experiments

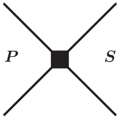
- High-intensity neutron & photon sources
- Cold neutrons
- Few-nucleon systems

EFT

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

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 independent structures

Danilov (1965, '71); Zhu et al. (2005); 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

MRS, Springer (2009)

Parity violation in chiral EFT

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

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

- PV in Compton scattering and pion production on the nucleon
- Pion-exchange contributions to NN potential

Kaplan, Savage (1993); Bedaque, Savage (2000); Chen, Ji (2001); Zhu et al. (2001)

Chiral PV *NN* potential

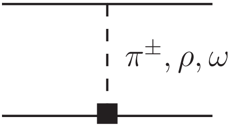
- $\mathcal{O}(Q^{-1})$:
  - one-pion exchange $\propto h_\pi$
- $\mathcal{O}(Q^{1})$:
  - Contact terms analogous to EFT($\not\pi$)
  - TPE $\propto h_\pi$
  - New $\gamma\pi NN$ contact interaction

Caveat: power counting assumes that h_π is not “small”

Savage, Springer (1998); Kaplan et al. (1999); Zhu et al. (2005); Viviani et al. (2014)

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)

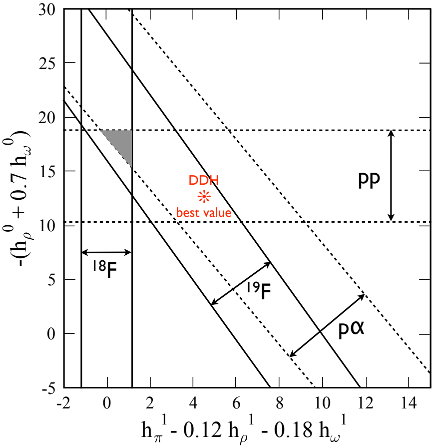
DDH potential

$$
\begin{aligned}
V_{\mathrm{DDH}} =& i\frac{h_\pi^1 g_A M}{\sqrt{2}F_\pi}\left(\frac{\vec{\tau}_1 \times \vec{\tau}_2}{2}\right)_z (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \left[\frac{\vec{p}_1 - \vec{p}_2}{2M}, w_\pi(r)\right] \\
& - g_\rho \left(h_\rho^0\, \vec{\tau}_1 \cdot \vec{\tau}_2 + h_\rho^1 \left(\frac{\vec{\tau}_1 + \vec{\tau}_2}{2}\right)_z + h_\rho^2\, \frac{3\tau_1^z\tau_2^z - \vec{\tau}_1 \cdot \vec{\tau}_2}{2\sqrt{6}} \right) \\
& \times \left((\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \left\{ \frac{\vec{p}_1 - \vec{p}_2}{2M}, w_\rho(r) \right\} + \cdots \right) \\
& + \cdots
\end{aligned}
$$

with

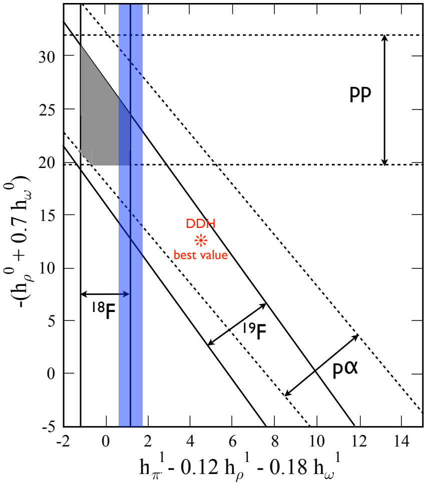
- g_M: strong (PC) meson-nucleon couplings
- h_M^i: weak (PV) meson-nucleon couplings
- $w_M(r) = \dfrac{\exp(-m_M r)}{4\pi r}$

Experimental constraints



Haxton, Holstein (2013)

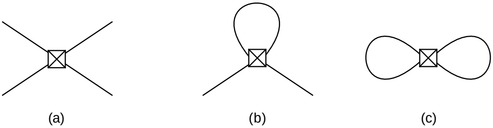
Inclusion of *pp* scattering at 221 MeV



Haxton, Holstein (2013)

PV on the lattice

- Determine PV couplings on lattice
- PV quark operators on lattice
- $$h_\pi = \left(1.099 \pm 0.505\,(\text{stat.})\,{}^{+0.058}_{-0.064}\,(\text{syst.})\right) \times 10^{-7}$$
- $m_\pi \sim 389\,\text{MeV}$, $L \sim 2.5\,\text{fm}$, $a_s \sim 0.123\,\text{fm}$
- Connected diagrams only
- Consistent with most model estimates, lower end of DDH "reasonable range"



Wasem (2012)

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

- Polarized beam on unpolarized target

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

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

Phillips, MRS, Springer (2009)

$\vec{n}p$ spin rotation

- Transmission of perpendicularly polarized beam

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

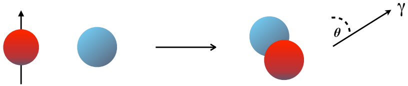
$$- [37.0 \pm 3.7]\,\Big(g^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} - 2g^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)}\Big)\Big\}\text{rad MeV}^{-\frac{1}{2}}$$

- Estimate

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

Grießhammer, MRS, Springer (2011)

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



- 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 $g^{({}^3S_1-{}^3P_1)}$

Savage (2001); MRS, Springer (2009)

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

- LO contribution purely from PV πN coupling
- LO EFT calculation using KSW

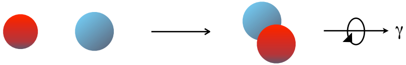
$$A_\gamma = 0.17 h_\pi$$

- Previous model calculations

$$A_\gamma = 0.11 h_\pi^1$$

Kaplan, Savage, Springer, Wise (1999); Desplanques, Missimer (1978)

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



- 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)

$np \to d\gamma$ amplitude

$$\begin{aligned}\mathcal{M} =& eXN^T\tau_2\sigma_2\left[\vec{\sigma}\cdot\vec{q}\,\boldsymbol{\epsilon}_d^*\cdot\boldsymbol{\epsilon}_\gamma^* - \vec{\sigma}\cdot\boldsymbol{\epsilon}_\gamma^*\,\vec{q}\cdot\boldsymbol{\epsilon}_d^*\right]N\\
&+ ieY\epsilon^{ijk}\boldsymbol{\epsilon}_d^{*\,i}\vec{q}^{\,j}\boldsymbol{\epsilon}_\gamma^{*\,k}\left(N^T\tau_2\tau_3\sigma_2N\right) + eE1_vN^T\sigma_2\vec{\sigma}\cdot\boldsymbol{\epsilon}_d^*\tau_2\tau_3N\vec{p}\cdot\boldsymbol{\epsilon}_\gamma^*\\
&+ ieW\epsilon^{ijk}\boldsymbol{\epsilon}_d^{*\,i}\boldsymbol{\epsilon}_\gamma^{*\,k}\left(N^T\tau_2\sigma_2\sigma^jN\right) + eV\boldsymbol{\epsilon}_d^*\cdot\boldsymbol{\epsilon}_\gamma^*\left(N^T\tau_2\tau_3\sigma_2N\right)\\
&+ ieU_1\epsilon^{ijk}k^i\boldsymbol{\epsilon}_\gamma^{*\,j}\boldsymbol{\epsilon}_d^{*\,k}N^T\sigma_2\vec{\sigma}\cdot\vec{p}\tau_2\tau_3N\\
&+ ieU_2\epsilon^{ijk}(\vec{k}\cdot\boldsymbol{\epsilon}_d^*\boldsymbol{\epsilon}_\gamma^{*\,i} - \boldsymbol{\epsilon}_\gamma^*\cdot\boldsymbol{\epsilon}_d^*k^i)p^jN^T\sigma_2\sigma_k\tau_2\tau_3N + \cdots\end{aligned}$$

- $X, E1_v, Y$: parity-conserving amplitudes
- V, W, U_1, U_2: parity-violating amplitudes
- Expansion of each amplitude: $Y = Y_{LO} + Y_{NLO} + \cdots$, etc

Kaplan, Savage, Springer, Wise (1999), Vanasse, MRS (2014)

A_L^γ in $\vec{\gamma}d \to np$ beyond threshold

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

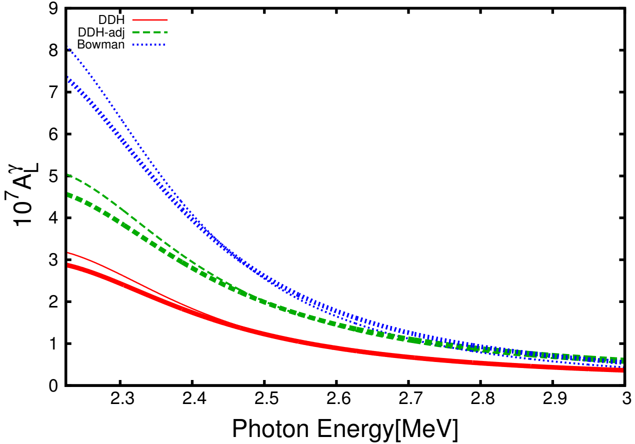
$$= 2\frac{M_N}{(\vec{p}^{\,2} + \gamma_t^2)} \frac{1}{|Y|^2 + |E1_v|^2 \frac{M_N^2 \vec{p}^{\,2}}{(\vec{p}^{\,2}+\gamma_t^2)^2}} \Bigg[\mathrm{Re}[Y^* V] + 2\mathrm{Re}[X^* W]$$

$$+ \frac{1}{3}\vec{p}^{\,2}\mathrm{Re}[E1_v^*(U_1 + 2U_2)] + \ldots \Bigg]$$

Vanasse, MRS (2014)

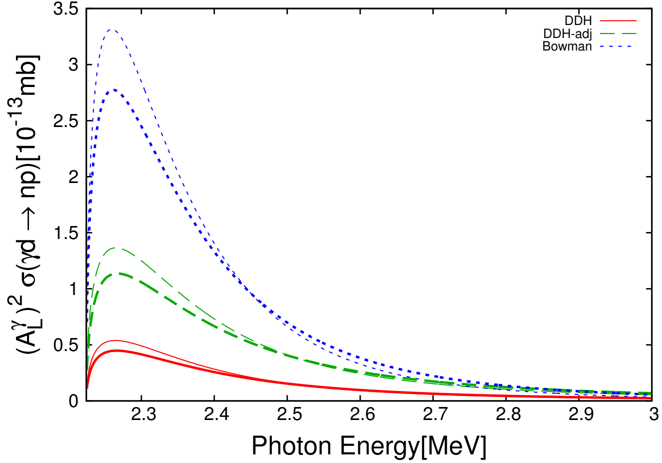
A_L^γ in EFT($\not\pi$): NLO results

- Fix PV couplings to model estimates
- "Reasonable ranges:" A_L^γ varies over orders of magnitude and sign



Where to measure?

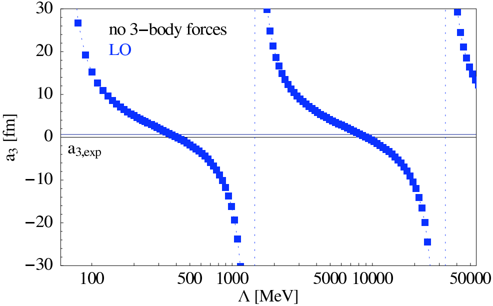
- A_L^γ max at threshold $\Rightarrow$ low count rate
- Simplified figure of merit $(A_L^\gamma)^2 \times \sigma(\gamma d \to np)$



- Maximized for $\omega \approx [2.259, 2.264]$ MeV

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

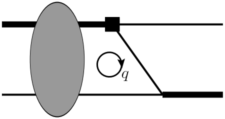


- Three-body counterterm at leading order
- PV three-body operators? Additional experimental input?

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

PV 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, MRS (2010)

PV three-body operators

Construct PV three-body operator for

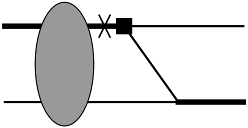
- *nd* system
- $S - P$ transitions (one derivative)
- Conserved J
- Isospin $\Delta I = 0, 1$

Two $^2S_{\frac{1}{2}} - {}^2P_{\frac{1}{2}}$ PV 3-body operators

- Different forms related by Fierz transformations
- Note: No $^2S_{\frac{1}{2}} - {}^4P_{\frac{1}{2}}$ contact operator

PV three-body operators at NLO

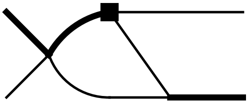
- NLO correction to PC sector suggests divergence



- Spin-isospin structure different from $S - P$ 3-body operator
- Cannot be absorbed by PV 3-body counterterm

No PV three-body operator at NLO

- Contribution from PC 3-body counterterm at same order

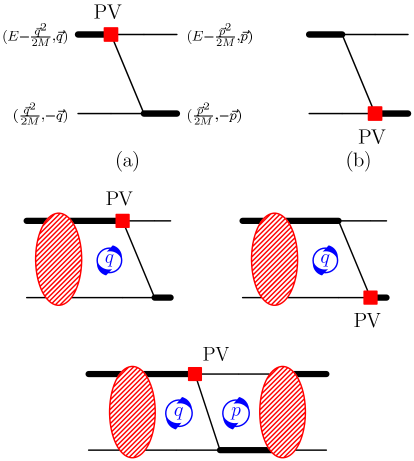


+ further diagrams

Grießhammer, MRS (2010)

PV $\vec{n}d$ scattering

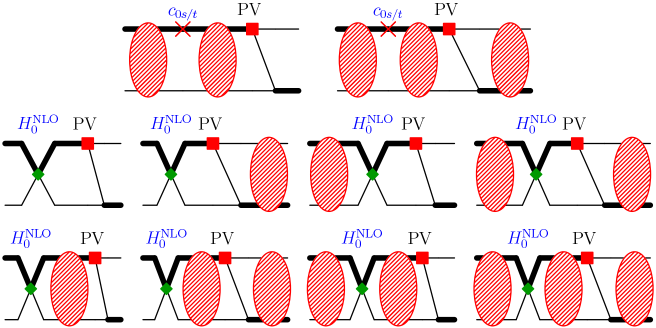
- $\vec{n}d$ scattering with one PV insertion
- Tree-level, “one-loop,” “two-loop” diagrams:



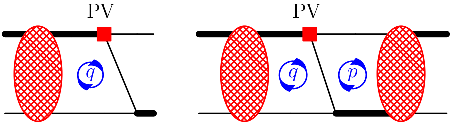
Grießhammer, MRS, Springer (2011); Vanasse (2011)

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

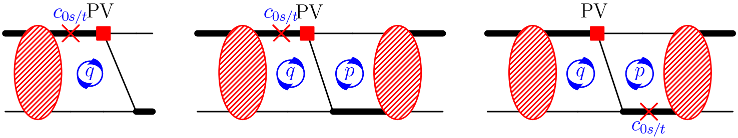
- NLO diagrams: “Class I”



- Reformulation in “partially resummed” formalism



- NLO diagrams: “Class II”



Neutron-deuteron spin rotation at NLO

- Spin-rotation angle

$$\frac{1}{\rho}\,\frac{d\phi^{nd}_{\mathrm{PV}}}{dL} = \Big([16.0 \pm 1.6]\, g^{({}^3S_1-{}^1P_1)} \;-\; [36.6 \pm 3.7]\;\; g^{({}^3S_1-{}^3P_1)}$$

$$+\;[4.6 \pm 1.0]\;\left(3g^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} - 2g^{({}^1S_0-{}^3P_0)}_{(\Delta I=1)}\right)\Big)\mathrm{rad\ MeV}^{-\frac{1}{2}}$$

- Estimate

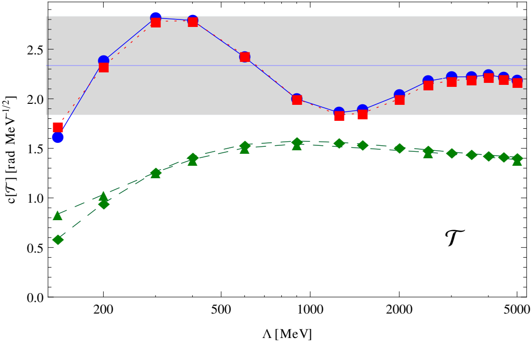
$$\left|\frac{\mathrm{d}\phi^{nd}_{\mathrm{PV}}}{\mathrm{d}L}\right| \approx \left[10^{-7}\cdots 10^{-6}\right]\;\frac{\mathrm{rad}}{\mathrm{m}}$$

Grießhammer, MRS, Springer (2011)

Uncertainty estimate

Estimate lower bounds on theoretical uncertainty

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



- Choose larger of two as error estimate

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($\not\pi$)/chiral EFT
- 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, 2014); 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
  - ${}^{6}\text{Li}(n,\alpha){}^{3}\text{H}$
  - ${}^{10}\text{B}(n,\alpha){}^{7}\text{Li}$
  - ${}^{10}\text{B}(n,\alpha){}^{7}\text{Li}^{*} \to {}^{7}\text{Li} + \gamma$
- 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
- EFT calculations for two- and three-nucleon observables
- No PV three-nucleon interactions at LO and NLO
- Consistent calculations in few-nucleon systems required
- Lattice QCD