Hadronic parity-violation in pionless effective field theory

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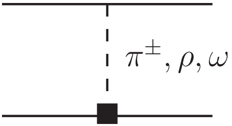
Nucleon-nucleon interactions

- Standard model describes interactions between quarks, gluons, W/Z,...
- For low-energy hadronic processes description in terms of fundamental degrees of freedom not convenient
- Instead use *NN* interactions: effective interaction between nucleons
- Manifestation of interaction between constituents of the nucleon

Parity violation in *NN* interactions

- Weak interaction between quarks introduces parity-violation (PV)
- Relative strength compared to strong effects $\sim G_F m_\pi^2 \approx 10^{-7}$
- Theoretical approaches
  - Danilov amplitudes: 5 $S - P$ partial wave transition amplitudes at low energy
  - Single-meson exchange between two nucleons with one strong and one weak vertex
  - DDH (interchange of $\pi^\pm$, ρ and ω mesons) approach has been standard for analyzing experiments



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B. Desplanques, J. F. Donoghue and B. R. Holstein, Annals Phys. **124**, 449 (1980)

DDH model

- Estimate weak couplings using symmetries and quark models: give range and best value
- Potential problems
    - Isovector coupling from ^{18}F small compared to DDH value
    - Isoscalar coupling from ^{133}Cs differs from other results
- Possible explanation: model assumptions not valid?
    - Restriction on spectrum
    - No two-pion-exchange
    - …

Effective field theories

- Low-energy approximation to a more fundamental theory
- Description in terms of relevant degrees of freedom (nucleons, pions, ...)
- Relies on separation of scales:

  $$Q \sim \text{mass, momentum, energy} < \text{some intrinsic scale } \Lambda$$

- Expansion in ratio of scales Q/Λ
- Model-independent: use most general Lagrangian compatible with symmetries
- Systematic inclusion of corrections
- Very successful for strong interactions: mesonic, one-, two- and few-nucleon sectors

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?

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M. J. Savage, Nucl. Phys. A **695**, 365 (2001)
M. J. Savage and R. P. Springer, Nucl. Phys. A **644**, 235 (1998) [Erratum-ibid. A **657**, 457 (1999)]
S. L. Zhu, C. M. Maekawa, B. R. Holstein, M. J. Ramsey-Musolf and U. van Kolck, Nucl. Phys. A **748**, 435 (2005)
C. P. Liu, Phys. Rev. C **75**, 065501 (2007)

Pionless EFT

- Existing and future experiments: $\sim$10s of MeV
  - *pp* scattering: $E = 13.6$ MeV (45 MeV)
  - NPDGamma (LANSCE, SNS): cold ($\sim$ meV) neutrons
  - Proposed: $\gamma d \to np$
- At energies $\lesssim m_\pi^2/M$: pion exchange not resolved
- Highly successful in parity-conserving sector
  - $np \to d\gamma$
  - *nd* scattering
  - ...

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G. Rupak, Nucl. Phys. A **678**, 405 (2000)
P. F. Bedaque, H. W. Hammer and U. van Kolck, Phys. Rev. C **58**, 641 (1998)
F. Gabbiani, P. F. Bedaque and H. W. Griesshammer, Nucl. Phys. A **675**, 601 (2000)

EFT($\not\pi$)Lagrangian

- Contact interactions with increasing number of (covariant) derivatives
- Lowest-order parity-conserving Lagrangian (partial-wave basis)

$$\begin{aligned}\mathcal{L} =& N^\dagger(i\partial_0 + \frac{\vec{\nabla}^2}{2M})N - \frac{1}{8}\mathcal{C}_0^{(^1S_0)}(N^T\tau_2\tau_a\sigma_2 N)^\dagger(N^T\tau_2\tau_a\sigma_2 N) \\ &- \frac{1}{8}\mathcal{C}_0^{(^3S_1)}(N^T\tau_2\sigma_2\sigma_i N)^\dagger(N^T\tau_2\sigma_2\sigma_i N) + \ldots,\end{aligned}$$

- Determine coupling constants by matching to effective range expansion

Lowest-order parity-violating Lagrangian

- Zhu *et. al.* : Lagrangian contains ten operators with corresponding low-energy constants
- Noted that at low energies only 5 combinations of these constants contribute
- Girlanda: only 5 independent operators exist

$$\mathcal{L}_{PV}^{Gir} = \Big\{ \mathcal{G}_1 (N^\dagger \vec{\sigma} N \cdot N^\dagger i \overleftrightarrow{\nabla} N - N^\dagger N N^\dagger i \overleftrightarrow{\nabla} \cdot \vec{\sigma} N)$$
$$- \tilde{\mathcal{G}}_1 \epsilon_{ijk} N^\dagger \sigma_i N \nabla_j (N^\dagger \sigma_k N)$$
$$- \mathcal{G}_2 \epsilon_{ijk} \left[N^\dagger \tau_3 \sigma_i N \nabla_j (N^\dagger \sigma_k N) + N^\dagger \sigma_i N \nabla_j (N^\dagger \tau_3 \sigma_k N) \right]$$
$$- \tilde{\mathcal{G}}_5 \mathcal{I}_{ab} \epsilon_{ijk} N^\dagger \tau_a \sigma_i N \nabla_j (N^\dagger \tau_b \sigma_k N)$$
$$+ \mathcal{G}_6 \epsilon_{ab3} \vec{\nabla} (N^\dagger \tau_a N) \cdot N^\dagger \tau_b \vec{\sigma} N \Big\}$$

where $\mathcal{I} = \text{diag}(1, 1, -2)$

L. Girlanda, Phys. Rev. C **77**, 067001 (2008)

Lowest-order parity-violating Lagrangian II

- Alternative form in partial wave basis

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

- Advantage: Each operator contributes to a specific partial wave

D. R. Phillips, M. R. S. and R. P. Springer, Nucl. Phys. A **822**, 14 (2009)

Lowest-order parity-violating Lagrangian III

- Lagrangians describe the same physics
- Can relate the coupling constants

$$\mathcal{C}^{(^3S_1-^1P_1)} = \frac{1}{4}(\mathcal{G}_1 - \tilde{\mathcal{G}}_1) \; ,$$

$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} = \frac{1}{4}(\mathcal{G}_1 + \tilde{\mathcal{G}}_1) \; ,$$

$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} = \frac{1}{2}\mathcal{G}_2 \; ,$$

$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)} = -\frac{1}{2}\tilde{\mathcal{G}}_5 \; ,$$

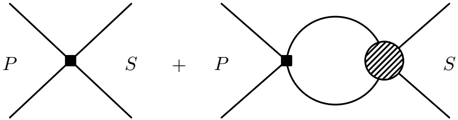
$$\mathcal{C}^{(^3S_1-^3P_1)} = \frac{1}{4}\mathcal{G}_6$$

Nucleon-nucleon scattering

- Simplest process
- $\vec{N}N$ 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

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

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

- No Coulomb interaction for *pp*
- Depends on ratio of PV and PC constant
  $\Rightarrow$ renormalization point (μ)-dependence of $\mathcal{A}_{pp/nn}$ dictated by $\mathcal{C}_0^{{}^1S_0}$

Leading-order results: *np*

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

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

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

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

- Measurement at 2 different energies gives 2 combinations of low-energy constants

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

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

X. Kong and F. Ravndal, Phys. Lett. B **450**, 320 (1999)

Comparison with experiment

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

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

- 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 only 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

P. D. Eversheim *et al.*, Phys. Lett. B **256** (1991) 11
S. Kistryn *et al.*, Phys. Rev. Lett. **58**, 1616 (1987)

Higher-order corrections

- At $E = 45$ MeV center-of-mass momentum $p > m_\pi$
- Use of dibaryon formalism in strong sector resums corrections proportional to effective range (formally of higher order)
- Re-analyze low-energy *pp* measurement (neglecting 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

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

$> 50\%$ difference

- Use dibaryon for PV contribution?

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

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

- Quantity of interest

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

- Do not use phenomenological wave function
-
$$A_\gamma = \frac{32}{3}\frac{M}{\kappa_1(1-\gamma a^{^1S_0})}\frac{\mathcal{C}^{(^3S_1-^3P_1)}}{\mathcal{C}_0^{^3S_1}}$$

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

M. R. S.,R. P. Springer, in preparation
M. J. Savage, Nucl. Phys. A **695**, 365 (2001)

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

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

- 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 $P_\gamma = 0$
- Proposals to use high-intensity free electron lasers for $\vec{\gamma} d \rightarrow np$

C. H. Hyun, J. W. Shin and S. Ando, arXiv:0809.4892 [nucl-th]
M. R. S.,R. P. Springer, in preparation
V. A. Knyazkov *et al.*, JETP Lett. **38**, 163 (1983)

Three-body observables: $\vec{n}d$ scattering

- $\vec{n}n$ scattering theoretically clean, but experimentally difficult
- Alternative: $\vec{n}d$ scattering
- Requires three-body treatment
- In parity-conserving case renormalization requires three-body counterterm at leading order
- Study renormalization for PV calculation
- Possible follow-up experiment to NPDGamma: $n + d \rightarrow t + \gamma$

P. F. Bedaque, H. W. Hammer and U. van Kolck, Nucl. Phys. A **676**, 357 (2000)

Conclusion & Outlook

- Parity violation in hadronic processes is manifestation of weak interaction between quarks
- Single-meson exchange model may to lead to inconsistencies
- Effective field theory allows for a model-independent analysis
- Very low energies of current and proposed experiments suited for EFT($\not\pi$)
- At lowest order there are 5 operators corresponding to $S - P$ wave transitions
- Corresponding low-energy constants have to be determined from experiment

Conclusion & Outlook

- Two-body processes well-suited for theoretical studies
- *pp* scattering gives access to one combination of low-energy constants
- Electromagnetic processes ($np \leftrightarrow d\gamma$) provide access to different combinations
- Study three-body processes such as *nd* scattering $\rightarrow$ renormalization?
- Four-body calculation in parity-conserving sector exists
- Higher-order Lagrangian: large number of terms (loss of parity restriction)?
- EFT($\not\pi$) as input in many-body calculations (e.g. no-core shell model, resonating group model)?
- Lattice? See talk by S. Beane

L. Platter, H. W. Hammer and U. G. Meissner, Phys. Lett. B **607**, 254 (2005)