Hadronic parity violation in few-nucleon systems

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Beyond the Standard Model Physics at low energies

- New physics at scale Λ_{new}
- For $E \ll \Lambda_{\text{new}}$: effective interactions with SM degrees of freedom
- Possible structure: local 4-quark operators $\bar{q}O_1q\,\bar{q}O_2q$
- In nuclei: isolate through symmetry violations
- QCD nonperturbative: manifestation of 4-quark operators at hadronic level?

Parity-violating NN interactions

- Hadronic manifestation of PV quark interactions
- Interplay of weak and nonperturbative strong interactions
- Range of weak interactions ~ 0.002 fm
  - Sensitive to quark-quark correlations inside nucleon
  - “Inside-out” probe: no need to go to high energies
- Relative strength in NN case ~ $G_F m_\pi^2 \approx 10^{-7}$
- Isolate through pseudoscalar observables ($\vec{p} \cdot \vec{\sigma}$)

Parity-violating NN interactions

- Meson-exchange model
  - Single-meson exchange (π,ρ,ω,…)
  - One parity-conserving, one parity-violating meson-nucleon coupling
  - Most common framework: DDH model
- Effective field theories
  - Pionless: 5 PV low-energy constants (LECs) at LO
  - Chiral: 1 PV πN LEC at LO, 5 PV NN LECs at NLO
- Experimental constraints very difficult to obtain

Danilov (1965, 1971); Desplanques, Donoghue, Holstein (1980); Kaplan, Savage (1993); Savage, Springer (1998); Zhu et al. (2005)

Parity-violating NN interactions in pionless EFT

- At very low energies: pion exchange not resolved
- Only nucleons as explicit degrees of freedom
- Contact terms with increasing number of derivatives
- Parity determined by orbital angular momentum L: $(-1)^L$
- Simplest PV interaction: $L \to L \pm 1$
- Leading order: five *S*-*P* transition operators with corresponding LECs

Danilov (1965, 1971); Girlanda (2008); Phillips, MRS, Springer (2009)

Parity-violating NN interactions in pionless EFT

- Five independent LECs at LO

$$C^{(^3S_1-^1P_1)}, \quad C^{(^1S_0-^3P_0)}_{(\Delta I=0)}, \quad C^{(^1S_0-^3P_0)}_{(\Delta I=1)}, \quad C^{(^1S_0-^3P_0)}_{(\Delta I=2)}, \quad C^{(^3S_1-^3P_1)}$$

- Parametrize short-distance details

- Determine from

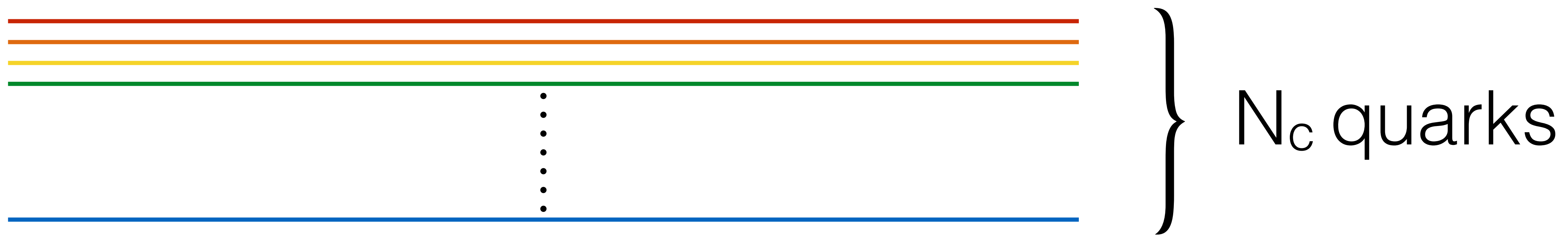
  - Underlying theory → nonperturbative QCD

  - Experimental results → suite of high-precision measurements in few-nucleon systems at very low energies

- Additional theoretical constraints?

Large-N_c QCD

- Generalize QCD from SU(3) to SU(N_c) gauge theory
- Taken with $g^2 N_c$ fixed
- Systematic expansion in $1/N_c$
- Phenomenologically successful
- Baryons
  - Bound states of N_c quarks
  - Baryon mass $M \sim O(N_c)$
  - Spectrum: (contracted) SU(4) spin-flavor symmetry $u\uparrow, u\downarrow, d\uparrow, d\downarrow$



't Hooft (1974); Witten (1979); Dashen, Jenkins, Manohar (1994)

Large-N_c QCD and effective field theories

- Capture some nonperturbative QCD aspects
- Based on symmetries
- Expansions in small parameter ($1/N_c$ vs p/Λ)
- Complementary
- Individually successful

Combine to obtain double expansion

- Large-N_c scaling of low-energy coefficients of EFT

Caveats

- Nuclear matter forms classical crystal for $N_c \to \infty$?
    - Assume that symmetries of NN interactions do not change
- Nucleon and Δ degenerate in large-N_c limit
- Δ plays important role in meson-baryon interactions
    - Ignore intermediate Δ states

Kaplan, Manohar (1997); Banerjee, Cohen, Gelman (2002)

PV NN interactions in the large-N_c expansion

- General operators structure

  - LO in N_c $[O(N_c)]$

$$\mathbf{p}_- \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)\vec{\tau}_1 \cdot \vec{\tau}_2$$

$$\mathbf{p}_- \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)[\tau_1 \tau_2]_2^{zz}$$

  - NLO in N_c $[O(N_c^0)]$

$$\mathbf{p}_+ \cdot (\vec{\sigma}_1 \tau_1^3 - \vec{\sigma}_2 \tau_2^3)$$

$$\mathbf{p}_- \cdot (\vec{\sigma}_1 + \vec{\sigma}_2)\ (\vec{\tau}_1 \times \vec{\tau}_2)^3$$

$$\mathbf{p}_- \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)\ (\vec{\tau}_1 + \vec{\tau}_2)^3$$

$$[(\mathbf{p}_+ \times \mathbf{p}_-) \cdot \vec{\sigma}_1\, \mathbf{p}_- \cdot \vec{\sigma}_2 + (\mathbf{p}_+ \times \mathbf{p}_-) \cdot \vec{\sigma}_2\, \mathbf{p}_- \cdot \vec{\sigma}_1]\ (\vec{\tau}_1 \times \vec{\tau}_2)^3$$

Phillips, Samart, Schat (2015)

PV NN interactions in the large-N$_c$ expansion

- NNLO in N_c $[O(N_c)]$

$$\mathbf{p}_- \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$$
$$\mathbf{p}_+^2 \; \mathbf{p}_- \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2) \; \vec{\tau}_1 \cdot \vec{\tau}_2$$
$$\mathbf{p}_+ \cdot (\vec{\sigma}_1 - \vec{\sigma}_2)$$
$$\mathbf{p}_+ \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \; \vec{\tau}_1 \cdot \vec{\tau}_2$$
$$\mathbf{p}_+ \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \; [\tau_1 \, \tau_2]_2^{zz}$$
$$\mathbf{p}_+^2 \; \mathbf{p}_- \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2) \; [\tau_1 \, \tau_2]_2^{zz}$$

- Can be multiplied by independent functions $U_i(\vec{p}_-^{\,2}) \sim O(1)$

Phillips, Samart, Schat (2015)

Parity violation in pionless EFT + large N_c

- Large-N_c scaling of PV couplings

$$\mathcal{C}^{({}^3S_1-{}^1P_1)} \sim N_c \quad \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} \sim N_c \quad \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)} \sim N_c \sin^2\theta_W$$
$$\mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=1)} \sim N_c^0 \sin^2\theta_W \quad \mathcal{C}^{({}^3S_1-{}^3P_1)} \sim N_c^0 \sin^2\theta_W$$

- Different terms related by Fierz transformations

$$\mathcal{C}^{({}^3S_1-{}^1P_1)} = 3\,\mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} \left[1 + O(1/N_c^2)\right]$$

- Only two independent terms at leading order in $1/N_c$ expansion

- Isotensor term is LO in combined expansion

- Isovector term (pion exchange) is NLO

MRS, Springer, Vanasse (2016)

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A New Paradigm for Hadronic Parity Nonconservation and Its Experimental Implications

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Comparison with experiment

- Longitudinal asymmetry in $\vec{p}p$ scattering and induced polarization in $np \to d\vec{\gamma}$:

$$\mathcal{C}^{(^3S_1-^1P_1)}/\mathcal{C} = (-1.1 \pm 1.0) \times 10^{-10}\,\mathrm{MeV}^{-}$$
$$\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}/\mathcal{C} = (7.4 \pm 2.3) \times 10^{-11}\,\mathrm{MeV}^{-1}$$

- γ-ray asymmetry in $\vec{n}p \to d\gamma$:

$$\mathcal{C}^{(^3S_1-^3P_1)}/\mathcal{C} = (-4.6 \pm 2.1) \times 10^{-11}\,\mathrm{MeV}^{-1}$$

- Large errors

- Not inconsistent with large-N_c expectation

Eversheim et al. (1991); Knyaz'kov (1983,84); Blyth et al. (2018); Richardson, MRS, Springer (2023)

Conclusions

- Parity violation in pionless EFT and large N_c
  - Two LECs at LO in combined pionless EFT and large-N_c expansion
  - Relationship between isoscalar LECs
  - Isovector LEC only NLO in large-N_c expansion, but isotensor LEC is LO
  - Trends, not predictions
  - Only upper limits on size
  - Other scales can impact relative sizes
  - LECs strongly depend on renormalization point
  - Renormalization-point dependence driven by S-wave interaction