PROCEEDINGS OF SCIENCE

Combining the large-N_C and low-momentum expansions to describe parity violation in few-nucleon systems

Jared Vanasse*
Stetson University
E-mail: jvanasse@stetson.edu

Parity-violating (PV) nucleon-nucleon (NN) interactions at low energies can be completely characterized by five low energy constants (LECs). The field of hadronic parity violation has long been plagued by uncertainties in these five LECs. Experiments to reliably extract these LECs are difficult as they involve few nucleon systems which give PV asymmetries roughly of the size 10^{-8} to 10^{-7}. Theoretically determining the low energy constants from the fundamental interactions of QCD is arguably more difficult, being hindered by the non-perturbative nature of QCD at low energies. In light of these facts, a theoretically motivated organizing principle for the relative size of the five LECs to guide future experiments would be highly desirable. Such an organizing principle has recently been provided by a large-N_C (number of colors) analysis of QCD, which is the subject of this paper. This large-N_C analysis serves both as a testable prediction from QCD and a possible organizing principle to assess the feasibility of future experiments.

The 9th International workshop on Chiral Dynamics
17-21 September 2018
Durham, NC, USA

*Speaker.

PoS(CD2018)111

1. Introduction

Parity-violating (PV) nucleon-nucleon (NN) interactions or hadronic parity violation in the Standard Model is mediated by the exchange of W and Z bosons and offers a unique probe of QCD. At energies below the Z-pole ($\sim$100 GeV) the exchange of Z and W bosons between quarks can be approximated by parity-violating effective four-quark interactions. At even lower energies ($E < \Lambda_{\text{QCD}}$) these four-quark interactions give rise to PV interactions between nucleons. Although PV interactions between nucleons are in principle calculable using the four-quark interactions with QCD, this is not currently practical at physical quark masses. Using the four-quark interactions a lattice QCD calculation of the $\Delta I = 2$ contribution to the PV NN interaction has been demonstrated at $m_\pi \sim 800$ MeV [1]. Future efforts will include calculating the finite volume effects and performing the renormalization of the bare matrix element [1]. Lattice calculations have also been performed for the PV pion exchange coupling at $m_\pi \sim 389$ MeV, but did not include disconnected diagrams [2].

The standard approach to hadronic parity violation has been through the so called DDH (Desplanques, Donoghue, and Holstein) model [3], which consists of seven phenomenological PV constants describing the exchange of the lightest scalar and vector mesons between nucleons. DDH provided "best guesses" and reasonable ranges for these unknown constants using quark model techniques and $SU(6)_W$ symmetry [4]. Other groups have attempted to estimate the size of the DDH coefficients using various theoretical techniques and fits to experiment [5, 6, 7, 8, 9]. Recently PV NN interactions have come to be described using effective field theories [10, 11]. EFTs offer a model independent approach to nuclear interactions, based on the underlying symmetries of QCD, with controlled error estimates for theoretical calculations.

At low energies ($E < m_\pi^2/M_N$) pions can be integrated out as degrees of freedom leaving a theory of NN interactions entirely in terms of nucleon fields. This theory known as pionless effective field theory (EFT($\not{\pi}$)) has been used to great success to describe properties of few-nucleon systems at low energies [12, 13]. At energies where EFT($\not{\pi}$) is valid the PV NN interaction is characterized by five low energy constants LECs [14, 15]. Many two- and three-nucleon PV observables have been calculated in the EFT($\not{\pi}$) framework [11]. At least five complimentary experiments need to be performed to completely characterize the PV NN interaction at low energies.

In order to have a clearer path forward both experimentally and theoretically in determining the PV LECs it is desirable to have an organizing principle by which the relative size of these LECs can be compared. Such a scheme is provided by large-N_C in QCD [16, 17], in which the number of colors in QCD can be used as an expansion parameter to investigate the relative size of interactions between nuclei. The large-N_C scaling of the general PV NN interaction was carried out by Phillips, Samart, and Schat (PSS) [18] and used to determine the large-N_C scaling of the DDH coefficients. Building on this work Schindler, Springer, and Vanasse (SSV) [19] found the large-N_C scaling of the five PV LECs in EFT($\not{\pi}$) by carefully using Fierz relations which mix terms of different large-N_C scaling. Finally, Gardner, Haxton, and Holstein (GHH) [20] used this large-N_C analysis to analyze available experimental data. The work of all three of these groups as well as a brief review of large-N_C counting for nuclear potentials is discussed below.

PoS(CD2018)111

2. Large-N_C scaling for nucleon-nucleon interactions

The general NN potential in the center-of-mass (c.m.) frame is given by

$$V(\mathbf{p}_-,\mathbf{p}_+) = \langle \mathbf{p}_{\text{out}},\gamma;-\mathbf{p}_{\text{out}},\delta|\hat{H}|\mathbf{p}_{\text{in}},\alpha;-\mathbf{p}_{\text{in}},\beta\rangle, \tag{2.1}$$

where α and β (γ and δ) represent the incoming (outgoing) nucleon's spin and isospin. $\hat{H}$ is the Hartree Hamiltonian [21, 22] (exact when $N_C \to \infty$ [17])

$$\hat{H} = N_C \sum_n \sum_{s,t} v_{stn} \left(\frac{\hat{S}}{N_C}\right)^s \left(\frac{\hat{I}}{N_C}\right)^t \left(\frac{\hat{G}}{N_C}\right)^{n-t-s}, \tag{2.2}$$

constructed from the bosonic quark operators (color has been summed over)

$$\hat{S}^i = \hat{q}^\dagger \frac{\sigma^i}{2}\hat{q}, \quad \hat{I}^a = \hat{q}^\dagger \frac{\tau^a}{2}\hat{q}, \quad \hat{G}^{ia} = \hat{q}^\dagger \frac{\sigma^i\tau^a}{2}\hat{q}. \tag{2.3}$$

The coefficients v_{stn} are functions of momentum that are $\mathscr{O}(1)$ in large-N_C. In the c.m. frame there are two different combinations of momenta that scale in large-N_C like

$$\mathbf{p}_- = \mathbf{p}_{\text{out}} - \mathbf{p}_{in} \sim N_C^0 \quad \mathbf{p}_+ = \mathbf{p}_{\text{out}} + \mathbf{p}_{\text{in}} \sim N_C^{-1}. \tag{2.4}$$

The momentum $\mathbf{p}_+$ is associated with relativistic corrections that bring a factor of $1/M_N$ leading to their large-N_C suppression relative to $\mathbf{p}_-$. The operators in the Hartree Hamiltonian have a large-N_C scaling of

$$\langle N'|\hat{S}/N_C|N\rangle \sim \langle N'|\hat{I}/N_C|N\rangle \sim N_C^{-1} \quad , \quad \langle N'|\hat{G}/N_C|N\rangle \sim \langle N'|\hat{\mathbf{1}}/N_C|N\rangle \sim 1. \tag{2.5}$$

Any term in a NN potential can be written in terms of products of these operators and momenta. Knowing the large-N_C scaling of the momenta and operators then allows for the determination of the large-N_C scaling of terms in the NN potential. The generic form for the parity conserving non-relativistic NN potential is[1]

$$V_{NN} = V_0^0 + V_\sigma^0 \vec{\sigma}_1\cdot\vec{\sigma}_2 + V_0^1 \vec{\tau}_1\cdot\vec{\tau}_2 + V_\sigma^1 \vec{\sigma}_1\cdot\vec{\sigma}_2 \vec{\tau}_1\cdot\vec{\tau}_2 + \cdots. \tag{2.6}$$

Matching these onto the operators $\hat{I}$, $\hat{S}$, and $\hat{G}$, Kaplan and Manohar [21] found the large-N_C scaling

$$V_0^0 \sim \hat{\mathbf{1}} \sim N_C, \quad V_\sigma^1 \sim \hat{G}\cdot\hat{G} \sim N_C, \quad V_\sigma^0 \sim \hat{S}\cdot\hat{S} \sim N_C^{-1}, \quad V_0^1 \sim \hat{I}\cdot\hat{I} \sim N_C^{-1}, \tag{2.7}$$

for these terms in the PC NN potential.

2.1 Large-N_C scaling of parity-violating nucleon-nucleon interaction

Using the methods outlined above PSS [18] calculated the large-N_C scaling of terms in the PV NN interaction. They found the $\mathscr{O}(N_C)$ operators

$$\begin{aligned} &\mathbf{p}_-\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)\vec{\tau}_1\cdot\vec{\tau}_2 \\ &\mathbf{p}_-\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)\mathscr{I}_{ab}\tau_1^a\tau_2^b, \end{aligned} \tag{2.8}$$

[1] For purposes of demonstrating large-N_C counting only some of the terms for the parity-conserving non-relativistic NN potential are shown in Eq. (2.6). Remaining terms can be seen in Ref. [21].

the $\mathscr{O}(N_C^0\sin^2\theta_W)$ operators, all $\Delta I=1$

$$\begin{aligned}&\mathbf{p}_+\cdot(\vec{\sigma}_1\tau_1^3-\vec{\sigma}_2\tau_2^3)\\&\mathbf{p}_-\cdot(\vec{\sigma}_1+\vec{\sigma}_2)(\vec{\tau}_1\times\vec{\tau}_2)^3\\&\mathbf{p}_-\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)(\vec{\tau}_1+\vec{\tau}_2)^3\\&\{(\mathbf{p}_+\times\mathbf{p}_-)\cdot\vec{\sigma}_1\mathbf{p}_-\cdot\vec{\sigma}_2+(\mathbf{p}_+\times\mathbf{p}_-)\cdot\vec{\sigma}_2\mathbf{p}_-\cdot\vec{\sigma}_1\}(\vec{\tau}_1\times\vec{\tau}_2)^3,\end{aligned}\tag{2.9}$$

and finally the $\mathscr{O}(N_C^{-1})$ operators

$$\begin{aligned}&\mathbf{p}_-\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)\\&\mathbf{p}_+^2\mathbf{p}_-\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)\vec{\tau}_1\cdot\vec{\tau}_2\\&\mathbf{p}_+\cdot(\vec{\sigma}_1-\vec{\sigma}_2)\\&\mathbf{p}_+\cdot(\vec{\sigma}_1-\vec{\sigma}_2)\vec{\tau}_1\cdot\vec{\tau}_2\\&\mathbf{p}_+\cdot(\vec{\sigma}_1-\vec{\sigma}_2)\mathscr{I}_{ab}\tau_1^a\tau_2^b\\&\mathbf{p}_+^2\mathbf{p}_-\cdot(\vec{\sigma}_1\times\vec{\sigma}_2)\mathscr{I}_{ab}\tau_1^a\tau_2^b,\end{aligned}\tag{2.10}$$

where $\mathscr{I}_{ab}=\mathrm{diag}[1,1,-2]$ gives an isotensor combination of nucleons. Factors of $\sin^2\theta_W$ come from the Standard Model Lagrangian for the effective four quark $\Delta I=1$ operators [23]. Note, the work of SSV [19] showed that there is also a $\sin^2\theta_W$ contribution to the isotensor part of the PV *NN* interactions. PSS did not have this factor on the isotensor term and it is not included in the summary of their results here.

With the large-N_C scaling of the generic PV *NN* potential, PSS matched their potential to the DDH potential obtaining

$$\begin{aligned}&h_\rho^0\sim\sqrt{N_c}\quad,\quad h_\rho^2\sim\sqrt{N_C}\\&\frac{h_\rho^{1'}}{\sin^2\theta_W}\lesssim\sqrt{N_C}\quad,\quad\frac{h_\omega^1}{\sin^2\theta_W}\sim\sqrt{N_C}\\&\frac{h_\rho^1}{\sin^2\theta_W}\lesssim\frac{1}{\sqrt{N_C}}\quad,\quad\frac{h_\pi^1}{\sin^2\theta_W}\lesssim\frac{1}{\sqrt{N_C}}\quad,\quad h_\omega^0\sim\frac{1}{\sqrt{N_C}},\end{aligned}\tag{2.11}$$

for the relative large-N_C scaling of the DDH coefficients. The large-N_C predictions are compared to the DDH "best guesses" and reasonable ranges in Fig. 1, where DDH parameters with a tilde have been rescaled by a factor $\sin^2\theta_W$. Due to the large reasonable ranges it is hard to make any firm conclusions on the validity of large-N_C. However, it is notable that the DDH "best guess" for $\tilde{h}_\rho^1$ and h_ω^0 are smaller than the DDH "best guess" for $\tilde{h}_\omega^1$, h_ρ^2, and h_ρ^0. The "best guess" for h_π^1 is in disagreement with large-N_C expectations but the reasonable range for h_π^1 is very large. The DDH parameter $h_\rho^{1'}$ is often ignored (including in DDH) as quark model calculations suggest it's small [24]. However, large-N_C gives no reason that $h_\rho^{1'}$ should be any smaller than h_π^1 or h_ω^0 [18].

2.2 Large-N_C scaling of parity-violating nucleon-nucleon interaction at low energies

Starting from all possible single derivative relativistic PV operators Girlanda [15] showed that there are only five independent non-relativistic single derivative operators by using Fierz relations,

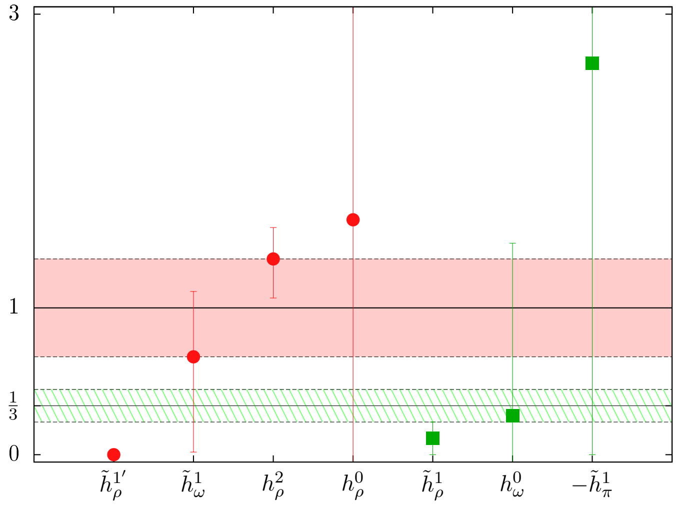

Figure 1: Comparison of DDH "best guesses" and ranges to large-N_C predictions. DDH parameters with a tilde have been divided by a factor of $\sin^2\theta_W = 0.24$ to make the large-N_C scaling manifest. The DDH "best guesses" for $\mathcal{O}(\sqrt{N_C})$ ($\mathcal{O}(1/\sqrt{N_C})$) DDH parameters are solid circles (squares) and the error bars give the DDH ranges. The error bands about 1 are $1/N_C$ and about $\frac{1}{3}$ $1/N_C^2$. To normalize the coefficients they have been divided by the average of $\tilde{h}_\omega^1$ and h_ρ^2.

the equations of motion, and a non-relativistic reduction yielding the five distinct terms

$$\begin{aligned}
\mathcal{L}_{PV}^{min} =& \mathcal{G}_1 (N^\dagger \vec{\sigma} N \cdot N^\dagger i \overleftrightarrow{\nabla} N - N^\dagger N N^\dagger \vec{\sigma} \cdot i \overleftrightarrow{\nabla} N) \\
& - \tilde{\mathcal{G}}_1 \epsilon_{ijk} N^\dagger \sigma^i N \nabla^j (N^\dagger \sigma^k N) \\
& - \mathcal{G}_2 \epsilon_{ijk} [N^\dagger \tau^3 \sigma^i N \nabla^j (N^\dagger \sigma^k N) + N^\dagger \sigma^i N \nabla^j (N^\dagger \tau^3 \sigma^k N)] \\
& - \mathcal{G}_5 \mathcal{I}_{ab} \epsilon_{ijk} N^\dagger \tau^a \sigma^i N \nabla^j (N^\dagger \tau^b \sigma^k N) \\
& + \mathcal{G}_6 \epsilon_{ab3} \vec{\nabla} (N^\dagger \tau^a N) \cdot (N^\dagger \tau^b \vec{\sigma} N).
\end{aligned} \tag{2.12}$$

Using Fierz rearrangements the Girlanda form of the Lagrangian can be written in a partial wave basis in which the incoming and outgoing angular momentum of the nucleons is manifest [25]

$$\begin{aligned}
\mathcal{L}_{PV} = -\Big[& \mathcal{C}^{(^3S_1-^1P_1)} \left(N^T \sigma^2 \vec{\sigma} \tau^2 N\right)^\dagger \cdot \left(N^T \sigma^2 \tau^2 i \overleftrightarrow{\nabla} N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} \left(N^T \sigma^2 \tau^2 \vec{\tau} N\right)^\dagger \left(N^T \sigma^2 \vec{\sigma} \cdot \tau^2 \vec{\tau} i \overleftrightarrow{\nabla} N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} \epsilon_{3ab} \left(N^T \sigma^2 \tau^2 \tau^a N\right)^\dagger \left(N^T \sigma^2 \vec{\sigma} \cdot \tau^2 \tau^b \overleftrightarrow{\nabla} N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)} \mathcal{I}_{ab} \left(N^T \sigma^2 \tau^2 \tau^a N\right)^\dagger \left(N^T \sigma^2 \vec{\sigma} \cdot \tau^2 \tau^b i \overleftrightarrow{\nabla} N\right) \\
& + \mathcal{C}^{(^3S_1-^3P_1)} \epsilon_{ijk} \left(N^T \sigma^2 \sigma^i \tau^2 N\right)^\dagger \left(N^T \sigma^2 \sigma^k \tau^2 \tau^3 \overleftrightarrow{\nabla}^j N\right) \Big] + \text{H.c.}.
\end{aligned} \tag{2.13}$$

Naive application of the large-N_C scaling of operators results in incorrect conclusions about the large-N_C scaling of the five PV LECs [19]. The issue arises from the fact that operators related by Fierz identities need not have the same large-N_C scaling as shown by SSV [19]. Since the basis of five PV LECs comes from Fierz relations on a more general set of operators, the actual large-N_C scaling of operators can be lost. For example, part of the PV potential is given by the terms

$$\begin{aligned} V =&\mathscr{A}_1^+\mathbf{p}_+\cdot(\vec{\sigma}_1-\vec{\sigma}_2)+\mathscr{A}_1^-\mathbf{p}_-\cdot i(\vec{\sigma}_1\times\vec{\sigma}_2) \\ &+\mathscr{A}_3^+\mathbf{p}_+\cdot(\vec{\sigma}_1-\vec{\sigma}_2)\vec{\tau}_1\cdot\vec{\tau}_2+\mathscr{A}_3^-\mathbf{p}_-\cdot i(\vec{\sigma}_1\times\vec{\sigma}_2)\vec{\tau}_1\cdot\vec{\tau}_2+\cdots \end{aligned} \tag{2.14}$$

Matching this potential to the Girlanda Lagrangian Eq. (2.12) gives the relations

$$\mathscr{G}_1=-\mathscr{A}_1^+\quad,\quad\tilde{\mathscr{G}}_1=-\mathscr{A}_1^-. \tag{2.15}$$

The large-N_C scaling, given in Eq. (2.10), of the operators $\mathscr{A}_1^+\sim N_C^{-1}$ and $\mathscr{A}_1^-\sim N_C^{-1}$ then gives

$$\mathscr{G}_1\sim\tilde{\mathscr{G}}_1\sim N_C^{-1}, \tag{2.16}$$

for the large-N_C scaling of the Girlanda LECs. However, using Fierz relations the operators $\mathscr{A}_3^+$ and $\mathscr{A}_3^-$ can be related to the operators $\mathscr{A}_1^+$ and $\mathscr{A}_-$ leading to the matching

$$\mathscr{G}_1=-\mathscr{A}_1^++\mathscr{A}_3^+-2\mathscr{A}_3^-\quad,\quad\tilde{\mathscr{G}}_1=-\mathscr{A}_1^--2\mathscr{A}_3^++\mathscr{A}_3^-. \tag{2.17}$$

Matching to Eqs. (2.10) and (2.8) gives the large-N_C scaling of the operators $\mathscr{A}_3^+\sim N_C^{-1}$ and $\mathscr{A}_3^-\sim N_C$, which gives

$$\mathscr{G}_1\sim\tilde{\mathscr{G}}_1\sim N_C \tag{2.18}$$

for the large-N_C scaling of the Girlanda LECs. In addition this large-N_C analysis implies the relation

$$\mathscr{G}_1=-2\tilde{\mathscr{G}}_1, \tag{2.19}$$

up to $\mathscr{O}(N_C^{-1})$. The lesson here is that one should start with the most general set of PV operators and then use Fierz identities to simplify them down to the set of five distinct operators, while keeping track of their dependence on the general set of operators. Then using the large-N_C scaling of the general set of operators the proper large-N_C scaling of the five operators can be properly discerned. This analysis carried out by SSV [19] gives

$$\mathscr{C}^{(^3S_1-^1P_1)}\sim\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\sim N_C\,, \tag{2.20}$$

$$\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\sim N_C\sin^2\theta_W\,, \tag{2.21}$$

$$\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\sim\mathscr{C}^{(^3S_1-^3P_1)}\sim N_C^0\sin^2\theta_W\,. \tag{2.22}$$

for the large-N_C scaling of the LECs in the partial wave basis with the additional relation

$$\mathscr{C}^{(^3S_1-^1P_1)}=3\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}, \tag{2.23}$$

that holds to $\mathscr{O}(N_C^{-1})$. Using the fact $\sin^2\theta_W\sim 0.24$ is similar to a factor of $1/N_C$ for $N_C=3$ Gardner, Haxton, and Holstein (GHH) defined the large-N_C basis of LECs [20]

$$C_1^{(N_C)}=\frac{1}{4}\mathscr{C}^{(^3S_1-^1P_1)}+\frac{3}{4}\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\qquad\mathrm{LO}(\mathscr{O}(N_C)) \tag{2.24}$$

$$C_2^{(N_C)}=\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\qquad\mathrm{LO}(\mathscr{O}(N_C)) \tag{2.25}$$

$$C_3^{(N_C)}=\frac{1}{4}\mathscr{C}^{(^3S_1-^1P_1)}-\frac{3}{4}\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\qquad\mathrm{NNLO}(\mathscr{O}(N_C^{-1})) \tag{2.26}$$

$$C_4^{(N_C)}=\mathscr{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\quad,\quad C_5^{(N_C)}=\mathscr{C}^{(^3S_1-^3P_1)}\qquad\mathrm{NNLO}(\mathscr{O}(N_C^0\sin^2\theta_W)) \tag{2.27}$$

in which the relationship in Eq. (2.23) was exploited. The GHH results quoted here do not include the factor $\sin^2\theta_W$ on the isotensor term later discovered by SSV. With an additional factor of $\sin^2\theta_W$ the LO $C_2^{(N_C)}$ terms would become NLO in the GHH counting. Using this hierarchy of PV LECs in large-N_C, GHH showed that the experimental data available at the time was in agreement with expectations from large-N_C. However, their analysis did not include the results from the NPDGamma collaboration [26] as they were unavailable at the time. In addition, the GHH analysis relied on use of the so called Rosetta Stone [27, 28] which matches different parametrizations of the PV LECs used in different calculations. However, this should be done with caution as different regulators used in different calculations can introduce spurious regulator dependence into the matching of PV LECs from different calculations [11]

3. Conclusions

Hadronic parity violation at low energies is described by five distinct LECs. Unfortunately, these LECs are difficult to determine both experimentally and theoretically. Lattice QCD offers an avenue to determine the values of these LECs from the fundamental interactions of QCD [2, 1]. Experimentally only pp scattering [29, 30] and the recent $\vec{n}p\to d\gamma$ [26] measurement have given non-zero results for PV asymmetries at low energies for few-body nuclear systems from which the PV LECs can be cleanly extracted. Another low energy "few-nucleon" experiment $\vec{n}+{}^3\text{He}\to p+{}^3\text{H}$ has been carried out at the Spallation Neutron Source at Oak Ridge National Laboratory and its data is currently being analyzed [31, 32]. Given the large amount of effort that goes into these experiments a guiding principle as to which experiments should be carried out would be desirable. A Large-N_C analysis from QCD of the relative size of the PV LECs in principle offers such a guiding principle. In addition large-N_C offers a testable prediction for the relative sizes of LECs from experiment.

The large-N_C analysis of SSV in the GHH basis shows that two of the five LECs dominate. However, a missing factor of $\sin^2\theta_W$ by SSV for the $\Delta I=2$ term not taken into account by GHH would mean that only one LEC is dominant in the GHH counting. By using the PV asymmetry of pp-scattering [29] at 13.6 MeV lab energies and the bound for the asymmetry of the circular polarization of photons in $n+p\to d+\vec{\gamma}$ [33], SSV demonstrated that the $\Delta I=2$ and $\Delta I=0$ PV NN interactions are roughly of the same size despite the $\sin^2\theta_W$ suppression of the $\Delta I=2$ term [19]. This suggests that $\sin^2\theta_W$ determined at the weak matching scale does not lead to significant suppression at hadronic scales [19]. With these considerations large-N_C determines that the five PV LECs are dominated by a linear combination of the $\Delta I=0$ PV NN interactions and the $\Delta I=2$ contribution. The photodisintegration of deuterium with circularly polarized photons is a possible future experiment at an upgraded High Intensity Gamma-Ray Source at the Triangle Universities Nuclear Laboratory [34]. This experiment has the advantage of being sensitive to the isotensor contribution of the PV NN interaction and the ideal energy at which it should be run has been assessed in EFT($\not{\pi}$) [35].

A preliminary updated GHH analysis including the more recent NPDGamma result [26] suggests that the large-N_C scaling is not wholly consistent with available experimental data [36]. In addition a recent three-nucleon EFT($\not{\pi}$) calculation using the recent NPDGamma result, the asymmetry from pp scattering [29], and a bound from pd scattering [30] also finds tension between

PoS(CD2018)111

current experimental data and the predicted large-N_C scaling [37]. This work also shows that a NLO (in EFT($\not\pi$)) PV three-nucleon force is necessary in contradiction with earlier claims [38]. Thus two- and three-nucleon PV observables can be described to a theoretical accuracy of $\sim$30% with only five two-nucleon LECs. However, to predict $\sim$10% or better for nuclear systems with $A \geq 3$ a PV three-nucleon force is necessary. This implies that the PV three-nucleon force in $A \geq 3$ systems is necessary if the N^{2}LO in large-N_C LECs are to be extracted from PV observables that contain LO in large-N_C LECs. Clearly further work is needed both experimentally and theoretically to further understand the picture of large-N_C in PV NN interactions.

References

[1] T. Kurth, E. Berkowitz, E. Rinaldi, P. Vranas, A. Nicholson, M. Strother et al., *Nuclear Parity Violation from Lattice QCD*, *PoS* **LATTICE2015** (2016) 329 [1511.02260].

[2] J. Wasem, *Lattice QCD Calculation of Nuclear Parity Violation*, *Phys. Rev.* **C85** (2012) 022501 [1108.1151].

[3] B. Desplanques, J. F. Donoghue and B. R. Holstein, *Unified Treatment of the Parity Violating Nuclear Force*, *Ann. Phys. (N.Y.)* **124** (1980) 449.

[4] H. J. Lipkin and S. Meshkov, *W-Spin and B-Spin Subgroups of SU(12)*, *Phys. Rev. Lett.* **14** (1965) 670.

[5] V. M. Dubovik and S. V. Zenkin, *FORMATION OF PARITY NONCONSERVING NUCLEAR FORCES IN THE STANDARD MODEL SU(2)(L) X U(1) X SU(3)(C)*, *Ann. Phys. (N.Y.)* **172** (1986) 100.

[6] G. B. Feldman, G. A. Crawford, J. Dubach and B. R. Holstein, *Delta contributions to the parity violating nuclear interaction*, *Phys. Rev. C* **43** (1991) 863.

[7] N. Kaiser and U. G. Meissner, *Novel Calculation of Weak Meson Nucleon Couplings*, *Nucl. Phys.* **A499** (1989) 699.

[8] U. G. Meissner and H. Weigel, *The Parity violating pion nucleon coupling constant from a realistic three flavor Skyrme model*, *Phys. Lett.* **B447** (1999) 1 [nucl-th/9807038].

[9] J. Bowman, *Hadronic weak interaction*, *INT program âĂIJFundamental Neutron PhysicsâĂİ* (2007) .

[10] S.-L. Zhu, C. M. Maekawa, B. R. Holstein, M. J. Ramsey-Musolf and U. van Kolck, *Nuclear parity-violation in effective field theory*, *Nucl. Phys. A* **748** (2005) 435 [nucl-th/0407087].

[11] M. R. Schindler and R. P. Springer, *The Theory of Parity Violation in Few-Nucleon Systems*, *Prog. Part. Nucl. Phys.* **72** (2013) 1 [1305.4190].

[12] S. R. Beane, P. F. Bedaque, W. C. Haxton, D. R. Phillips and M. J. Savage, *From hadrons to nuclei: Crossing the border*, nucl-th/0008064.

[13] J. Vanasse, *Three-body systems in pionless effective field theory*, *Int. J. Mod. Phys.* **E25** (2016) 1641002 [1609.03086].

[14] G. Danilov, *Circular polarization of γ quanta in absorption of neutrons by protons and isotopic structure of weak interactions*, *Physics Letters* **18** (1965) 40 .

[15] L. Girlanda, *On a redundancy in the parity-violating 2-nucleon contact Lagrangian*, *Phys. Rev. C* **77** (2008) 067001 [0804.0772].

[16] G. 't Hooft, *A Planar Diagram Theory for Strong Interactions*, *Nucl. Phys.* **B72** (1974) 461.

[17] E. Witten, *Baryons in the 1/n Expansion*, *Nucl. Phys.* **B160** (1979) 57.

[18] D. R. Phillips, D. Samart and C. Schat, *Parity-Violating Nucleon-Nucleon Force in the 1/N_c Expansion*, *Phys. Rev. Lett.* **114** (2015) 062301 [1410.1157].

[19] M. R. Schindler, R. P. Springer and J. Vanasse, *Large-N_c limit reduces the number of independent few-body parity-violating low-energy constants in pionless effective field theory*, *Phys. Rev.* **C93** (2016) 025502 [1510.07598].

[20] S. Gardner, W. C. Haxton and B. R. Holstein, *A New Paradigm for Hadronic Parity Nonconservation and its Experimental Implications*, *Ann. Rev. Nucl. Part. Sci.* **67** (2017) 69 [1704.02617].

[21] D. B. Kaplan and A. V. Manohar, *The Nucleon-nucleon potential in the 1/N(c) expansion*, *Phys. Rev.* **C56** (1997) 76 [nucl-th/9612021].

[22] R. F. Dashen, E. E. Jenkins and A. V. Manohar, *Spin flavor structure of large N(c) baryons*, *Phys. Rev.* **D51** (1995) 3697 [hep-ph/9411234].

[23] J. F. Donoghue, E. Golowich and B. R. Holstein, *Dynamics of the standard model*, *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* **2** (1992) 1.

[24] B. R. Holstein, *NUCLEAR PARITY VIOLATION PARAMETER H (RHO) (1)'*, *Phys. Rev.* **D23** (1981) 1618.

[25] D. R. Phillips, M. R. Schindler and R. P. Springer, *An effective-field-theory analysis of low-energy parity- violation in nucleon-nucleon scattering*, *Nucl. Phys. A* **822** (2009) 1 [0812.2073].

[26] NPDGAMMA collaboration, *First Observation of P-odd γ Asymmetry in Polarized Neutron Capture on Hydrogen*, *Phys. Rev. Lett.* **121** (2018) 242002 [1807.10192].

[27] J. Vanasse, *Parity Violation in nd Interactions*, *Phys. Rev. C* **86** (2012) 014001 [1110.1039].

[28] W. C. Haxton and B. R. Holstein, *Hadronic Parity Violation*, *Prog. Part. Nucl. Phys.* **71** (2013) 185 [1303.4132].

[29] P. D. Eversheim et al., *Parity violation in proton proton scattering at 13.6-MeV*, *Phys. Lett.* **B256** (1991) 11.

[30] D. E. Nagle, J. D. Bowman, C. Hoffman, J. McKibben, R. Mischke, J. M. Potter et al., *Parity violation in the scattering of 15 MeV protons by hydrogen*, *AIP Conf. Proc.* **51** (1979) 224.

[31] N. Fomin, *Hadronic Weak Interaction Studies at the SNS*, *EPJ Web Conf.* **113** (2016) 01007.

[32] M. Gericke, $n+^3 he$, *KITP Workshop on Hadronic Parity Violation (HPNC)* (2018) .

[33] V. A. Knyaz'kov, E. A. Kolomenskii, V. M. Lobashev, V. A. Nazarenko, A. N. Pirozhkov, A. I. Shablii et al., *A new experimental study of the circular polarization of np capture gamma-rays*, *Nucl. Phys.* **A417** (1984) 209.

[34] M. W. Ahmed, A. E. Champagne, B. R. Holstein, C. R. Howell, W. M. Snow, R. P. Springer et al., *Parity Violation in Photonuclear Reactions at HIGS – Submission to Snowmass 2013: Intensity Frontier*, in *Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013*, 2013, 1307.8178, http://www.slac.stanford.edu/econf/C1307292/docs/submittedArxivFiles/1307.8178.pdf.

[35] J. Vanasse and M. R. Schindler, *Energy dependence of the parity-violating asymmetry of circularly polarized photons in $d\vec{\gamma} \to np$ in pionless effective field theory*, *Phys. Rev.* **C90** (2014) 044001 [1404.0658].

[36] W. Haxton, *Large-nc hpnc analyses post npdgamma*, *CIPANP 2018* (2018) .

[37] J. Vanasse, *Parity-Violating Three Nucleon Interactions at Low Energies and Large-N_C*, 1809.10740.

[38] H. W. Grießhammer and M. R. Schindler, *On Parity-Violating Three-Nucleon Interactions and the Predictive Power of Few-Nucleon EFT at Very Low Energies*, Eur. Phys. J. A **46** (2010) 73 [1007.0734].