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Hadronic Parity Violation in Few-Nucleon Systems

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Abstract The weak interaction between quarks induces a parity-violating component in the interactions between nucleons, which is typically suppressed by a factor of \( \approx 10^{-7} \) compared to the dominant parity-conserving part. Because of the short range of the weak interactions, it provides a unique probe of the strong dynamics that confine quarks into nucleons. An experimental program to map out this weak component of the nuclear force is underway at a number of facilities, including the Spallation Neutron Source at Oak Ridge National Laboratory. The corresponding observables are related to few-nucleon processes at very low energies, at which pionless effective field theory provides a reliable and model-independent theoretical approach to hadronic parity violation. Results in two- and three-nucleon systems, the role of parity-violating three-nucleon forces, and possible extensions to other few-nucleon systems are discussed.

1 Introduction

While the forces between nucleons are dominated by the strong and electromagnetic interactions and thus conserve parity, weak quark-quark interactions induce a parity-violating (PV) component in the nucleon-nucleon interactions. For reviews see, e.g., Refs. [1, 24, 29]. Compared to the parity-conserving (PC) part of the interaction, the PV component of the interaction is expected to be suppressed by a factor of roughly \( 10^{-6} \) to \( 10^{-7} \). To isolate such small effects, one considers observables that would vanish if parity was conserved in the interactions. Examples include longitudinal and angular asymmetries as well as induced polarizations in scattering, break-up, and capture reactions. These pseudoscalar observables are sensitive to a correlation between spin and momentum \( (\sigma \cdot p) \). Parity-violating effects can be enhanced by several orders of magnitude when considering heavier nuclei in which energy levels with opposite parity are closely spaced (see, e.g., Ref. [7]). However, the nuclear structure in general complicates the analysis and interpretation of these effects in terms of the underlying nucleon-nucleon interactions. With the increased availability of high-luminosity, low-energy sources of neutrons and photons, considerable attention has been devoted to study hadronic parity violation in few-nucleon systems, for which calculations in terms of two- and possibly three-nucleon forces are feasible.

Traditionally, PV observables have been analyzed in terms of a meson-exchange framework. In the seminal work of Ref. [11] (commonly referred to as “DDH”) a PV potential is formulated in terms of single \( \pi, \rho \), and \( \omega \) exchanges between two nucleons, with one parity-conserving and one parity-violating meson-nucleon coupling. While the PC meson-nucleon couplings are well-established, the authors of Ref. [11] estimated “reasonable ranges” for the PV couplings based on quark model and symmetry consid-

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erations. The DDH potential has been combined with a number of PC potentials; see, e.g., Refs. [1,24,29]
for applications. More recently, starting with the work of Refs. [20,27], PV nucleon-nucleon interactions
have been formulated and applied in the framework of effective field theory (EFT), with a comprehensive
analysis of PV interactions in the so-called pionless and chiral EFTs performed in Ref. [35]. The advan-
tage of the EFT approach is that it is model independent and that it provides a framework to consistently
treat parity-conserving and parity-violating two-, three-, and few-nucleon interactions, as well as external
currents.

2 Parity Violation in Pionless EFT

Most of the experimentally accessible processes involve very low energies well below the pion mass. At these
energies, it is possible to formulate a so-called “pionless EFT” (EFT(π/3)) solely in terms of nucleons as active
degrees of freedom. All other hadrons, including pions, are integrated out and their contributions are taken
into account through the values of the so-called low-energy couplings (LECs) of the nucleon contact terms.
See, e.g., Refs. [3,4,23] for reviews. In the PV sector, the leading-order Lagrangian consists of five indepen-
dent terms [15,22]; in the formalism including auxiliary dibaryon fields for NN S-wave states it takes the
form [30]

\[ L_{PV} = -g^{(3S_1-1P_1)} d_t \left( N^T \sigma_2 \tau_2 iD_i N \right) \]

\[ + g^{(1S_0-3P_0)} d_s \left( N^T \sigma_2 \sigma_1 \tau_2 \tau_A iD_i N \right) \]

\[ + g^{(3S_0-3P_0)} \epsilon^{3AB} d_s \left( N^T \sigma_2 \sigma_1 \tau_2 \tau_B D_i N \right) \]

\[ + g^{(1S_0-3P_0)} \epsilon^{ijk} d_t \left( N^T \sigma_2 \sigma_1 \tau_2 \tau_3 D^j N \right) \]

\[ + \text{h.c.} + \ldots, \quad (1) \]

where \( a \, O \, D_i \, b = a \, O \, D_j \, b - (D_i a) O b \) with \( O \) some spin-isospin-operator, and \( I = \text{diag}(1, 1, -2) \).

The LECs \( g \) are unknown parameters in the EFT framework and have to be determined from a calculation in terms of
the underlying standard model degrees of freedom or from comparison with experiment. Once they have been
determined, the Lagrangian of Eq. (1) together with the corresponding Lagrangian in the PC sector can be used
to predict PV observables. At present no theoretical determination of the LECs exists; therefore, the extraction
from comparison with experimental data seems more feasible. This requires the consistent calculation of at
least five PV observables within the pionless EFT framework. Results of an ongoing program with this goal
are described in the following. While different conventions have been used in the individual calculations, all
results presented here are adjusted to the conventions of Ref. [17].

3 Two-Nucleon Systems

The longitudinal asymmetry in the scattering of polarized nucleons off an unpolarized nucleon target is defined as

\[ A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad (2) \]

where \( \sigma_{\pm} \) is the total cross section for the scattering of nucleons with helicity \( \pm 1 \). At leading order in EFT(\( \mathcal{F} \))
the asymmetries for \( \uparrow \uparrow \rightarrow \downarrow \downarrow \), \( \uparrow \downarrow \rightarrow \downarrow \uparrow \), and \( \uparrow \downarrow \rightarrow \downarrow \downarrow \) scattering are given by [19,22,35]
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\[ A_{L}^{nn} = -\sqrt{\frac{32M}{\pi}} p \left( g^{(1S_0-3P_0)}_{(\Delta l=0)} - g^{(1S_0-3P_0)}_{(\Delta l=2)} + g^{(1S_1-3P_0)}_{(\Delta l=1)} \right), \]

\[ A_{L}^{pp} = -\sqrt{\frac{32M}{\pi}} p \left( g^{(1S_0-3P_0)}_{(\Delta l=0)} + g^{(1S_0-3P_0)}_{(\Delta l=1)} + g^{(1S_0-3P_0)}_{(\Delta l=2)} \right), \]

\[ A_{L}^{np} = -\sqrt{\frac{32M}{\pi}} p \frac{\partial g^{(1S_0-3P_0)}_{(\Delta l=0)}}{\partial \Omega} + \frac{3 \partial g^{(1S_0-3P_0)}_{(\Delta l=0)}}{\partial \Omega} \left( g^{(1S_0-3P_0)}_{(\Delta l=0)} - 2g^{(1S_0-3P_0)}_{(\Delta l=2)} \right) \]

\[ -\sqrt{\frac{32M}{\pi}} p \frac{\partial g^{(1S_0-3P_0)}_{(\Delta l=0)}}{\partial \Omega} + \frac{3 \partial g^{(1S_0-3P_0)}_{(\Delta l=0)}}{\partial \Omega} \left( g^{(1S_0-3P_0)}_{(\Delta l=1)} + 2g^{(1S_0-3P_0)}_{(\Delta l=2)} \right) \]

where \( M \) is the nucleon mass and \( p \) the nucleon momentum in the center-of-mass frame. Coulomb interactions are not considered in the \( pp \) result of Eq. (3). As shown in Ref. [22], they amount to a correction of about 3\% or less at the energies and angular ranges that have been considered experimentally.

The result for \( np \) scattering is related to another observable, the spin rotation angle in the transmission of a perpendicularly polarized neutron beam through a proton target. Up to next-to-leading order (NLO), the result for the rotation angle per unit length is [17]

\[ \frac{1}{\rho} \frac{d\phi_{PV}}{dl} = 4\sqrt{2\pi M} \left( \frac{g^{(3S_1-3P_1)}_{(\Delta l=0)}}{\gamma_1} + \frac{1}{2} \frac{g^{(1S_0-3P_0)}_{(\Delta l=0)}}{\gamma_1} \right) = 4\sqrt{2\pi M} \left( \frac{g^{(3S_1-3P_1)}_{(\Delta l=0)}}{\gamma_1} + \frac{1}{2} \frac{g^{(1S_0-3P_0)}_{(\Delta l=0)}}{\gamma_1} \right), \]

where \( \rho \) is the target density, \( \gamma_{1/s} \) are the poles in the NN scattering amplitudes in the \( ^3S_1 \) and \( ^1S_0 \) channels, respectively, and \( Z_{1/s} = \frac{1}{1 - \frac{1}{\gamma_{1/s}}} \), with \( r_{1/s} \) the effective ranges in the corresponding channels.

In addition to reactions involving only nucleons, hadronic parity violation can also be studied in processes involving external photons. Considerable experimental effort has been devoted to measuring the photon angular asymmetry \( A_{\gamma} \) in polarized neutron capture, \( n + p \rightarrow d \gamma \), with a currently ongoing experiment at Oak Ridge’s Spallation Neutron Source [14]. The angular asymmetry is defined through

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = 1 + A_{\gamma} \cos\theta, \]

with \( \theta \) the angle between the spin of the incoming neutron and the direction of the outgoing photon. In EFT(\( \varphi \)), \( A_{\gamma} \) has been calculated in Refs. [26,30]. Adjusted to the conventions used here, the result at LO is

\[ A_{\gamma} = \frac{4}{3} \sqrt{\frac{M^2}{\pi}} \frac{1}{\kappa_1 (1 - \gamma_1 a_1)} g^{(5S_1-3P_1)}_\gamma, \]

where \( \kappa_1 \) is the anomalous nucleon isovector magnetic moment and \( a_1 \) the scattering length in the \( ^1S_0 \) channel.

Another PV observable can be determined from the induced circular polarization in the capture of unpolarized neutrons, \( n + p \rightarrow d \gamma' \). The polarization is defined by

\[ P_{\gamma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \]

where \( \sigma_{\pm} \) is the total cross section for outgoing photons with helicity \( \pm 1 \). The EFT(\( \varphi \)) result at threshold is [30]

\[ P_{\gamma} = -2\sqrt{\frac{2}{\pi}} \frac{M^2}{\kappa_1 (1 - \gamma_1 a_1)} \left[ \left( 1 - \frac{2\gamma_1 a_1}{3} \right) g^{(3S_1-3P_1)}_\gamma + \frac{\gamma_1 a_1}{3} \left( 2g^{(1S_0-3P_0)}_{(\Delta l=0)} - g^{(1S_0-3P_0)}_{(\Delta l=2)} \right) \right]. \]

As seen by comparing Eqs. (6) and (8), the observables \( A_{\gamma} \) and \( P_{\gamma} \) are independent and provide complementary information on the PV couplings. Experimentally, it might be more feasible to measure the asymmetry \( A_{\gamma} \) in the inverse reaction, \( \gamma' d \rightarrow np \), which is equal to \( P_{\gamma} \) for exactly reversed kinematics. A model calculation found strong dependence of \( A_{\gamma} \) on the choice of which PC two-nucleon model is used in the evaluation [28]. The measurement of \( A_{\gamma} \) is currently being considered as a flagship experiment for a possible upgrade of the HIGS facility at the Triangle Universities Nuclear Laboratory.
4 Three-Nucleon Systems

One of the advantages of the EFT approach is the ability to estimate the relative strengths of two- and three-nucleon (3N) interactions based on power counting. In the PC sector, naive application of the power counting rules predicts that the leading 3N interactions are suppressed and start to contribute at next-to-next-to-leading order (NNLO). However, it was shown that for the case of \(nd\) scattering in the \(^2S_1^2\) channel a 3N interaction is needed at LO to remove cutoff dependence in the results for the scattering amplitude [5,6]. In the PV sector, 3N interactions are similarly predicted to first appear at NNLO. However, the unexpected “promotion” of the 3N terms in the PC sector raises the question whether PV 3N interactions have to be considered at lower orders than naively expected. Reference [16] showed by analyzing \(Nd\) scattering that no PV 3N interaction terms are required at LO and NLO for the renormalization of the scattering amplitude. This implies that up to an estimated accuracy of \(\approx 10\%\) even three- and other few-nucleon observables can be analyzed in terms of PV two-nucleon interactions, and no additional terms have to be taken into account.

Theoretical considerations of Ref. [16] are confirmed by the calculation of PV \(nd\) scattering in Refs. [17,32]. The results for the scattering amplitude can be related to the spin rotation angle of polarized neutrons in a deuteron target. The rotation angle per unit length up to NLO is given by [17]

\[
\frac{1}{\rho} \frac{d\phi}{dl} = \left( [16 \pm 1.6] g_{S_1-1P_1} + [34 \pm 3.4] g_{S_1-3P_1} + [4.6 \pm 1.0] \left( 3g_{(\Delta I=0)} - 2g_{(\Delta I=1)} \right) \right) \text{rad MeV}^{-1},
\]

including theoretical error estimates. Reference [32] also contains a LO result for the longitudinal asymmetry in \(\vec{n}d\) scattering.

5 Other Few-Body Systems

A number of further few-body systems provide the opportunity to study hadronic parity violation. Measurement of a PV angular asymmetry in the charge-exchange reaction \(\vec{n} + \vec{^3He} \rightarrow \vec{^3H} + p\) is planned at the SNS in the near future [8]. Model and hybrid calculations of the asymmetry exist [33,18], but a consistent EFT calculation has not been performed to date. Experimental results exist for the longitudinal asymmetry in \(\vec{p}^4\text{He}\) scattering [21] and \(n^4\text{He}\) spin rotation [31]. Corresponding model calculations can be found in Refs. [25,13] and [2,12], respectively. Consistent EFT calculations of these observables are desirable, and the necessary few-body techniques continue to be developed, putting this goal within reach.

6 Conclusions and Outlook

Because of its origin in the interplay of short-range weak and strong interactions at low energy, hadronic parity violation offers a unique probe of nonperturbative QCD. The use of EFT(\(\pi/\)) provides a unified framework to treat PC and PV interactions as well as external currents on the same footing. In addition, the EFT power counting provides a method to estimate theoretical errors. Up to NLO, PV NN interactions in EFT(\(\pi/\)) can be parameterized in terms of five independent couplings, corresponding to five S-P wave transitions in the two-nucleon system. These couplings are not determined within the EFT, but can be determined from comparison with experimental results. The presented results form part of a comprehensive study of PV observables in few-nucleon systems that will allow a consistent and model-independent analysis and interpretation of hadronic parity violation. A first preliminary determination of a PV pion-nucleon coupling from lattice QCD can be found in Ref. [34]. This presents an important step in the determination of the PV couplings in terms of the underlying framework of the standard model. Additional EFT(\(\pi/\)) calculations of PV observables in few-nucleon systems will further constrain the unknown couplings and will help in improving our understanding of hadronic parity violation.

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