

# Hadronic parity violation in few-nucleon systems

M R Schindler

Department of Physics and Astronomy, University of South Carolina, Columbia, SC, 29208, USA

E-mail: mschindl@mailbox.sc.edu

**Abstract.** The interactions between nucleons contain a parity-violating component, which originates in the weak interaction between quarks and which is suppressed by a factor of approximately  $10^{-7}$  compared to the dominant parity-conserving component. A theoretical framework based on effective field theory methods to analyze and interpret parity-violating interactions between nucleons is described and a number of applications are discussed.

## 1. Introduction

Interactions between nucleons are the manifestations of the underlying interactions between the constituents of the nucleons. In addition to the parity-conserving (PC) strong and electromagnetic interactions, quarks also interact weakly. The interplay between weak quark-quark interactions and the strong interactions that confine the quarks into nucleons results in a parity-violating (PV) component in the nucleon-nucleon (NN) force. Because of the short range of the weak interaction of about 0.002 fm compared to the typical size of the nucleon of about 1 fm, the PV component of the NN interactions is sensitive to short-range correlations between quarks and can be considered a probe of nonperturbative QCD. However, the PV component of the NN interactions is typically suppressed by a factor of the order of  $10^{-7}$ , making a detection of these effects challenging. It can be isolated by considering pseudo-scalar observables that would vanish if parity was conserved, such as longitudinal or angular asymmetries. For reviews, see, e.g., Refs. [1, 2, 3, 4].

Parity-violating effects can be enhanced by several orders of magnitude in heavier nuclei (see, e.g., Ref. [5]), but the analysis and interpretation of these results is complicated by nuclear structure effects. The ongoing developments in high-intensity neutron and photon sources and improved experimental control of systematics has made measurements of hadronic parity violation in few-nucleon systems possible. These systems can be analyzed in terms of two- and three-nucleon interactions without the complexities of nuclear structure. The following describes a program to analyze hadronic parity violation in few-nucleon systems that is based on effective field theory (EFT), and selected results are presented.

## 2. Hadronic parity violation in pionless effective field theory

Experiments aimed at PV observables typically involve very low energies much below the pion mass. At these energies, pion exchange between nucleons cannot be resolved. It is therefore possible to “integrate out” not just heavy hadrons, but also pions, and to formulate an EFT for nucleon interactions in which the only dynamical degrees of freedom are nucleons. The resulting



“pionless EFT” or EFT( $\pi$ ), consisting of contact terms with an increasing number of derivatives, has been very successful in describing low-energy observables, including electromagnetic effects. See, e.g., Refs. [6, 7, 8] for reviews.

In the PV sector, the leading-order (LO) Lagrangian contains five independent terms that describe the transition from two nucleons in an S-wave state to a P-wave state and vice versa [9, 10]. In a formulation that introduces an auxiliary dibaryon field for S-wave NN states, it is given by [11]

$$\begin{aligned} \mathcal{L}_{PV} = & - \left[ g^{(3S_1-1P_1)} d_t^{i\dagger} \left( N^T \sigma_2 \tau_2 i \overleftrightarrow{D}_i N \right) + g_{(\Delta I=0)}^{(1S_0-3P_0)} d_s^{A\dagger} \left( N^T \sigma_2 \sigma_i \tau_2 \tau_A i \overleftrightarrow{D}_i N \right) \right. \\ & + g_{(\Delta I=1)}^{(1S_0-3P_0)} \epsilon^{3AB} d_s^{A\dagger} \left( N^T \sigma_2 \sigma_i \tau_2 \tau^B \overleftrightarrow{D}_i N \right) + g_{(\Delta I=2)}^{(1S_0-3P_0)} \mathcal{I}^{AB} d_s^{A\dagger} \left( N^T \sigma_2 \sigma_i \tau_2 \tau^B i \overleftrightarrow{D}_i N \right) \\ & \left. + g^{(3S_1-3P_1)} \epsilon^{ijk} d_t^{i\dagger} \left( N^T \sigma_2 \sigma^k \tau_2 \tau_3 \overleftrightarrow{D}^j N \right) \right] + \text{h.c.} + \dots, \end{aligned} \quad (1)$$

where  $a \overleftrightarrow{O} D_i b = a \mathcal{O} D_i b - (D_i a) \mathcal{O} b$ , with  $\mathcal{O}$  some spin-isospin-operator, and  $\mathcal{I} = \text{diag}(1, 1, -2)$ . The ellipsis stands for higher-order terms, which will not be considered here. The five low-energy constants (LECs)  $g^{(X-Y)}$  encode the short-distance details of the interactions. In principle, they can be expressed in terms of parameters of the Standard Model. However, this requires a calculation in the nonperturbative regime of QCD, which has not been feasible yet. As an alternative, the LECs can be obtained by comparison with experimental results. A prerequisite for such a determination is a sufficient number of measured observables in low-energy few-nucleon systems.

### 3. Two-nucleon systems

Reactions involving two nucleons provide the simplest systems in which to study PV NN interactions. In the case of scattering of a polarized beam and an unpolarized target, the PV longitudinal asymmetry  $A_L$  is given by

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

where  $\sigma_{\pm}$  is the total cross section for beams with helicity  $\pm 1$ . The LO results in EFT( $\pi$ ) for various beam and target nucleons are [12, 13, 10]

$$\begin{aligned} A_L^{nn} &= -\sqrt{\frac{32M}{\pi}} p \left( g_{(\Delta I=0)}^{(1S_0-3P_0)} - g_{(\Delta I=1)}^{(1S_0-3P_0)} + g_{(\Delta I=2)}^{(1S_0-3P_0)} \right), \\ A_L^{pp} &= -\sqrt{\frac{32M}{\pi}} p \left( g_{(\Delta I=0)}^{(1S_0-3P_0)} + g_{(\Delta I=1)}^{(1S_0-3P_0)} + g_{(\Delta I=2)}^{(1S_0-3P_0)} \right), \\ A_L^{np} &= -\sqrt{\frac{32M}{\pi}} p \frac{\frac{d\sigma^{1S_0}}{d\Omega}}{\frac{d\sigma^{1S_0}}{d\Omega} + 3 \frac{d\sigma^{3S_1}}{d\Omega}} \left( g_{(\Delta I=0)}^{(1S_0-3P_0)} - 2g_{(\Delta I=2)}^{(1S_0-3P_0)} \right) \\ &\quad - \sqrt{\frac{32M}{\pi}} p \frac{\frac{d\sigma^{3S_1}}{d\Omega}}{\frac{d\sigma^{1S_0}}{d\Omega} + 3 \frac{d\sigma^{3S_1}}{d\Omega}} \left( g^{(3S_1-1P_1)} + 2g^{(3S_1-3P_1)} \right), \end{aligned} \quad (3)$$

where  $M$  is the nucleon mass and  $p$  the nucleon momentum in the center-of-mass frame. Coulomb effects are neglected in the case of  $pp$  scattering. They can be included consistently in the EFT( $\pi$ ) formalism, but as shown in Ref. [10] only amount to corrections on the order of 3% even at the lowest energy for which the asymmetry has been measured experimentally.

The asymmetry in  $np$  scattering is related to another PV observable, the spin rotation angle per unit length in the transmission of perpendicularly polarized neutrons through an unpolarized hydrogen target. At next-to-leading order (NLO) in the EFT( $\pi$ ) expansion it is given by

$$\frac{1}{\rho} \frac{d\phi_{\text{PV}}^{np}}{dl} = 4\sqrt{2\pi M} \left( \frac{2g^{(3S_1-3P_1)} + g^{(3S_1-1P_1)}}{\gamma_t} \frac{Z_t + 1}{2} + \frac{g_{(\Delta I=0)}^{(1S_0-3P_0)} - 2g_{(\Delta I=2)}^{(1S_0-3P_0)}}{\gamma_s} \frac{Z_s + 1}{2} \right), \quad (4)$$

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

In addition, reactions including photons can also be used to study hadronic parity violation. The angular asymmetry  $A_\gamma$  of outgoing photons in the radiative capture of polarized neutrons on protons,  $\vec{n}p \rightarrow d\gamma$ , is currently being determined by the NPDGamma collaboration at Oak Ridge National Laboratory [14]. At LO the EFT( $\pi$ ) result is given by [15, 11]

$$A_\gamma = \frac{4}{3} \sqrt{\frac{2}{\pi}} \frac{M^{\frac{3}{2}}}{\kappa_1 (1 - \gamma_t a_s)} g^{(3S_1-3P_1)}, \quad (5)$$

where  $\kappa_1$  is the anomalous nucleon isovector magnetic moment and  $a_s$  the scattering length in the  $^1S_0$  channel.

A complementary and independent observable can be measure in the unpolarized capture of neutrons by measuring the circular polarization  $P_\gamma$  of the outgoing photons,  $np \rightarrow d\vec{\gamma}$ . For exactly reversed kinematics, it is identical to the asymmetry  $A_L^\gamma$  in deuteron break-up by polarized photons,  $\vec{\gamma}d \rightarrow np$ ,

$$A_L^\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad (6)$$

where  $\sigma_\pm$  denotes the total break-up cross section for photons with  $\pm$  helicity. The energy dependence of  $A_L^\gamma$  has been determined in EFT( $\pi$ ) to NLO in Ref. [16]. A measurement of  $A_L^\gamma$  would place stringent demands on the intensity and control of the beam as well as on the control of systematic effects. The possibility of performing such an experiment at an upgraded High Intensity Gamma-Ray Source (HIGS) at the Triangle Universities Nuclear Laboratory is currently being considered. To aid these efforts, Ref. [16] considers two simplified figures of merit to determine at which energy to best perform a measurement. Using order of magnitude estimates for the unknown PV LECs indicates that the preferred energy range is 2.26 MeV to 2.3 MeV.

#### 4. Three-nucleon systems

In the PC sector of EFT( $\pi$ ), naive dimensional analysis does not predict three-nucleon interactions at LO. However, it was shown that a three-nucleon term is enhanced compared to this naive power counting and should be taken into account already at LO [17, 18]. The corresponding LEC can be determined from the experimental value of, e.g., the three-nucleon binding energy or the  $nd$  scattering length.

In Ref. [19] it was shown that such an enhancement does not occur in the PV sector of the theory and that PV three-nucleon interactions do not have to be included when considering nucleon-deuteron scattering at LO and NLO. This means that up to an accuracy of approximately 10% pseudoscalar few-nucleon observables can be described in terms of PV two-nucleon interactions alone.

The  $\vec{n}d$  spin rotation angle was determined in EFT( $\pi$ ) to LO and NLO in Refs. [20, 21], with the NLO results given by [20]

$$\frac{1}{\rho} \frac{d\phi_{PV}^{nd}}{dl} = \left( [16 \pm 1.6]g^{(^3S_1-^1P_1)} + [34 \pm 3.4]g^{(^3S_1-^3P_1)} + [4.6 \pm 1.0](3g_{(\Delta I=0)}^{(^1S_0-^3P_0)} - 2g_{(\Delta I=1)}^{(^1S_0-^3P_0)}) \right) \frac{\text{rad}}{\text{MeV}^{\frac{1}{2}}}, \quad (7)$$

where the uncertainties represent theoretical error estimates.

## 5. Conclusions and outlook

Parity-violating NN interactions originate in the interplay of weak and nonperturbative strong quark-quark interactions and therefore provide a unique probe of nonperturbative QCD. At energies below the pion mass, EFT( $\pi$ ) can be used as a unified framework to describe PC and PV interactions as well as external currents in few-nucleon reactions. All short-distance physics is encoded in the LECs of the theory. An effort is underway to determine the five LO LECs from a suite of measurements in few-nucleon systems. These numbers provide a nontrivial target that any calculation in the nonperturbative regime has to reproduce. Currently, lattice QCD provides a framework for such calculations, and a first calculation of a PV coupling was performed in Ref. [22]. Further work in this direction will be of great importance.

In addition to the results presented here, there are a number of further observables in four- and five-nucleon systems for which experimental results exist. Examples include  $\vec{p}$   $^4\text{He}$  scattering [23] and the neutron spin rotation angle in a  $^4\text{He}$  target [24]. A calculation in terms of an EFT including dynamical pion degrees of freedom was performed for the PV asymmetry in the charge-exchange reaction  $^3\text{He}(\vec{n}, p)^3\text{H}$  [25], and the corresponding experiment is planned at Oak Ridge National Laboratory.

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