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Hadronic Parity Violation in Few-Nucleon Systems

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-
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 advantage 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/0)) 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 independent terms [15, 22]; in the formalism including auxiliary dibaryon fields for NN S-wave states it takes the form [30]

\[
\mathcal{L}_{PV} = - g(3S_1-1P_1) d_i^{+} \left( N^T \sigma_2 \tau_2 i \vec{D}_i \vec{N} \right) \\
+ g(1S_0-3P_0) d_s^{A\uparrow} \left( N^T \sigma_2 \tau_2 \tau_A i \vec{D}_i \vec{N} \right) \\
+ g(1S_0-3P_0) \epsilon^{3AB} d_s^{A\uparrow} \left( N^T \sigma_2 \tau_2 \tau_B i \vec{D}_i \vec{N} \right) \\
+ g(1S_0-3P_0) \mathcal{I}^{AB} d_s^{A\uparrow} \left( N^T \sigma_2 \tau_2 \tau_B i \vec{D}_i \vec{N} \right) \\
+ g(3S_1-3P_1) \epsilon^{ijk} d_i^{+} \left( N^T \sigma_2 \tau_2 \tau_3 i \vec{D}_j \vec{D}_k \vec{N} \right) \] + h.c. + ... ,
\]

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

\[
A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-},
\]

where \( \sigma_{\pm} \) is the total cross section for the scattering of nucleons with helicity \( \pm 1 \). At leading order in EFT(\( \pi/0 \)) the asymmetries for \( \vec{n} \ n, \vec{p} \ p, \) and \( \vec{n} \ p \) scattering are given by [19, 22, 35]

1 This is the field-theoretic formulation of the Danilov amplitudes [9, 10].