Chiral effective theory description of hadronic parity violation in few-nucleon systems

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Weak interactions at the quark level induce a parity-violating (PV) component in the nucleon-nucleon potential, which is currently the object of several experimental programs involving few-nucleon systems at cold neutron facilities, such as the Los Alamos Neutron Science Center, the National Institute of Standards and Technology (NIST) Center for Neutron Research and the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The expected magnitude of weak effects in such systems is very tiny, of relative order of 10^{-7}. However, the ability to perform ab-initio calculations together with improved experimental techniques allow to foresee a complete characterization of this component of the nuclear interaction in the near future. Traditionally, hadronic parity violation in nuclear systems has been analyzed by means of a meson-exchange model, the DDH model [1]. More recently, the effective field theory paradigm has provided a model-independent framework, directly linked to the underlying QCD and weak dynamics through their symmetry properties, in particular chiral symmetry. Weak interactions break chiral symmetry in a definite way at the quark level. PV nuclear interactions emerge in the effective theory by including in the effective Lagrangian operators which exhibit the same pattern of chiral symmetry breaking as at the quark level. Within this description, valid at sufficiently low energy, the nuclear interaction consists of multipion exchanges and contact interactions among nucleons. In a pioneering work Kaplan and Savage [2] wrote down the pion-nucleon effective Lagrangian up to next-to-leading order. This Lagrangian includes at leading order (LO) a pion-nucleon interaction without derivatives with an associated low-energy constant (LEC) denoted as h^1_π. One of the tasks of the above mentioned experimental programs is precisely the determination of this LEC, of which only rough order of magnitude estimates exist to date. The PV nucleon-nucleon contact Lagrangian at LO has been constructed in Ref. [3], and consists of 5 independent operators with corresponding LECs. In Ref. [4] we construct the PV pion-nucleon Lagrangian at next-to-next-to-leading order (N2LO) and we derive the PV NN potential at the same order, in the framework of recoil-corrected time-ordered perturbation theory. Diagrams contributing up to N2LO are shown in Fig. 1. Diagrams in panel (a) starts at $O(Q^{-1})$, Q denoting a generic low-momentum, and it involves the LEC h^1_π. Up to $O(Q)$ it includes relativistic corrections, and subleading parity-conserving (PC) as well as PV $\pi - N$ couplings. The latter however can be absorbed into a redefinition of the contribution (CT), which involves the 5 short-distance LECs and is of order $O(Q)$. Diagrams (b) and (c) involve a combination of PC contact interaction with a PV pion-exchange. While formally of order $O(Q)$ they infact vanish at this order. Diagrams (d)-(g) involve two-pion exchanges. The loops are regulated in dimensional regularization and the infinities can be absorbed by a renormalization of the LECs appearing in panel (CT). The "box" contribution (g) must be isolated from the iterated one-pion exchange by also taking into account the recoil corrections. Diagrams (h)-(u) contribute to the renormalization of h^1_π In all the PV potential depends on 6 LECs, h^1_π and the 5 short distance LECs of Ref. [3].

With this potential we calculated some PV observables in $A = 2 - 4$ systems. To this aim we used, for the PC component of the nuclear interaction the Entem-Machleidt N3LO chiral potential [5] for two values of the cutoff $\Lambda = 500$ MeV and 600 MeV, in conjunction, for the $A > 2$ systems with the chiral N2LO three-nucleon interaction, with the same cutoff as used for the

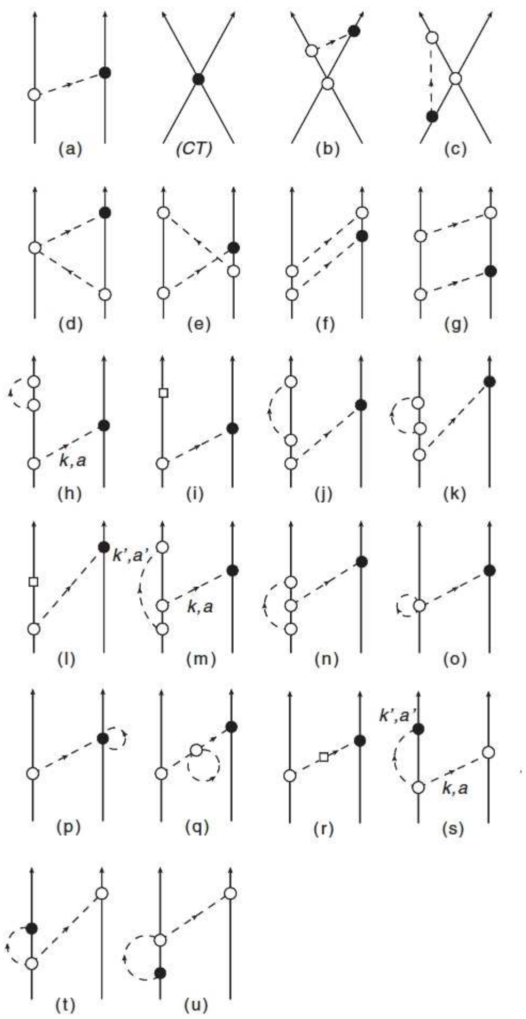

Figure 1. Diagrams contributing to the PV NN potential up to N2LO. Nucleons and pions are denoted by solid and dashed lines respectively. The open and solid circles represent parity-conserving and parity-violating vertices. Only one time ordering is shown for a given topology.

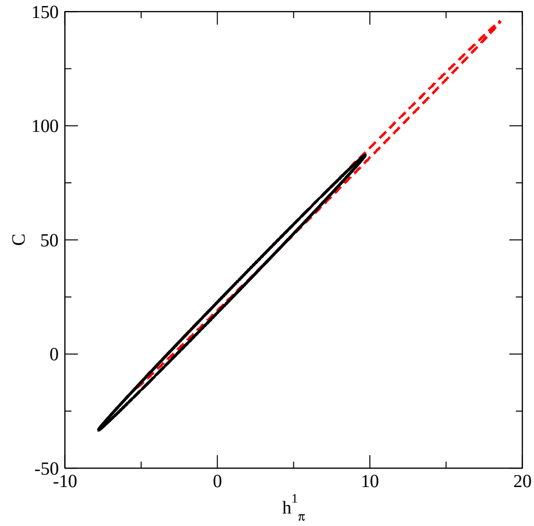

Figure 2. Contours corresponding to $\chi^2 = 2$ for the $\vec{p} - p$ longitudinal asymmetry. The black-solid and red-dashed lines correspond respectively to the cutoffs $\Lambda = 500$ MeV and $\Lambda = 600$ MeV. The values for the LECs are in units of 10^{-7}.

NN interaction, adjusted to reproduce the $A = 3$ binding energies and the Gamow-Teller matrix element in tritium β decay. By fitting currently available measurements of the $\vec{p} - p$ longitudinal asymmetry we obtain the constraint shown in Fig. 2 between h^1_π and the combination of contact LECs $C = C_1 + C_2 + 2(C_4 + C_5)$. We also considered the neutron spin rotation $d\phi/dz$ in the transverse plane, as polarized neutron travel along z on p and d targets, for vanishing neutron energy. We expressed this observable as a linear combination of the 6 PV LECs and found that the $\vec{n} - p$ spin rotation is sensitive to all the LECs (especially to C_5) except C_4, while $\vec{n} - d$ is especially sensitive to h^1_π, C_2 and C_3. Its measurement could be very useful in constraining their values.

Finally we considered the longitudinal asymmetry A_z for the reaction $^3\text{He}(\vec{n}, p)^3\text{H}$, also for ultracold neutrons, which is given by $A_z = a_z \cos(\theta)$, θ being the angle between the outgoing proton momentum and the neutron beam direction. Expressing a_z as a linear combination of the 6 LECs we found that it is mostly sensitive to h^1_π, C_2, C_3 and C_4. Once the h^1_π will be known, from the measurement of the PV asymmetry a_γ in $^1\text{H}(\vec{n}, \gamma)^2\text{H}$ radiative capture in the ongoing NPDGAMMA experiment [6], which is known to be very sensitive to this observable, the outlined measurements of PV observables in few-nucleon systems would thus allow to put strong constraints on the PV LECs.

REFERENCES

1. B. Desplanques, J. F. Donoghue and B. R. Holstein, Annals Phys. **124**, 449 (1980).
2. D. B. Kaplan and M. J. Savage, Nucl. Phys. A **556**, 653 (1993) [Erratum-ibid. A **570**, 833 (1994)] [Erratum-ibid. A **580**, 679 (1994)].
3. L. Girlanda, Phys. Rev. C **77**, 067001 (2008) [arXiv:0804.0772 [nucl-th]].
4. M. Viviani, A. Baroni, L. Girlanda, A. Kievsky, L. E. Marcucci and R. Schiavilla, Phys. Rev. C **89**, no. 6, 064004 (2014) [arXiv:1403.2267 [nucl-th]].
5. R. Machleidt and D. R. Entem, Phys. Rept. **503**, 1 (2011) [arXiv:1105.2919 [nucl-th]].
6. R. Alarcon *et al.* [NPDgamma Collaboration], EPJ Web Conf. **66**, 05001 (2014).