Parity-violating nucleon-nucleon interaction

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The understanding of weak interaction, while satisfactory at the level of quarks and leptons, is complicated in the hadronic sector by the non-perturbative character of QCD in this regime. At the nuclear level, weak interactions can only be studied by analyzing small effects induced by characteristic properties of this interaction, like flavour changing or parity violation. There remain indeed many puzzles in the domain of hadronic weak interactions (HWI), such as the origin of the $\Delta I = 1/2$ rule in the non-leptonic decays of kaons and hyperons, largely dominated by transition amplitudes with $\Delta I = 1/2$, the difficulties in describing simultaneously the S- and P-waves of hyperon non-leptonic decays, and the anomalously large parity-violating asymmetries in the radiative hyperon decays. All these problems involve the strange quark and might be ascribed to a lack of convergence of the SU(3) chiral series. In order to isolate the genuine properties of HWI, without being much affected by the presence of dynamical strange quarks, it is therefore interesting to focus on the $\Delta S = 0$ component of HWI, by examining the hadronic parity violation (HPV).

In this respect, few-nucleon systems provide a clean theoretical laboratory, due to the possibility of performing accurate *ab initio* calculations. Improved experimental techniques allow now to measure on such systems the tiny effects of HPV, which are of the order of $G_F m_\pi^2 \sim O(10^{-7})$.

The traditional framework for the analysis of HPV has been, for almost three decades, the meson-exchange parity-violating NN potential of Desplanques, Donoghue and Holstein (DDH), which incorporates π, ρ and ω exchanges. It is parametrized by 7 parity-violating meson-nucleon couplings, to be determined from experiment. However, the consistency between different experiments, analyzed on the basis of this interaction, is not entirely satisfactory. A more modern point of view has been advocated recently in Ref. [1], by recasting HPV in the language of effective field theory (EFT). This has the advantage of being a model-independent approach, based on the separation of the physical scales involved in the problem: subleading corrections can in principle be evaluated systematically in a $p/\Lambda_{\rm H}$ expansion, p being the typical momentum and $\Lambda_{\rm H}$ the hadronic scale, characteristic of hadrons whose mass is not protected by chiral symmetry. It is then ideally suited for a situation in which experimental data are scarce. In addition to the (strong) parity-conserving couplings of chiral perturbation theory, one has to consider the induced parity-violating (PV) couplings from weak interactions. Virtual W and Z exchanges induce (at the quark level) four-quark, current-current operators in the effective hamiltonian, which have definite transformation rules under the broken chiral symmetry of strong interactions. Hadronic operators, built in terms of pions and nucleons, are therefore introduced in the effective theory, with the same transformation properties, yielding a PV effective Lagrangian, whose infinite number of terms is ordered according to the power counting of chiral perturbation theory.

In the present line of research, on one hand we reexamine critically the basic ingredients of the analysis of [1], on the other hand we employ an accurate numerical technique for the resolution of the few-nucleon Schroedinger equation, to provide a sensitivity study of relevant physical observables to the values of the involved LECs.

The starting point is the form of the PV effective Lagrangian. For our purposes it takes the following general form,

$$\mathcal{L}^{\rm PV} = \mathcal{L}^{\rm PV}_{\pi N} + \mathcal{L}^{\rm PV}_{NN}, \qquad (1)$$

where the first term contains the interaction of pions with a single nucleon, and the second one contains 2-nucleon contact vertices. The contact Lagrangian was already derived, in its minimal form in Refs. [2,3]: it consists of only five independent operators, contrary to previous claims in the literature [1]. As for the pion-nucleon component, it is necessary to consider $\Delta I = 0, 1, 2$ PV terms of chiral dimension up to two. Preliminary studies in this respect [4] point towards the absence of an independent dimension-two PV πN coupling, which was instead advocated in Ref. [1]. Indeed, it can be shown that such a coupling would violate the general requirements of Poincaré covariance[1] All these observations imply that the effective description of HPV is much more constrained (and therefore predictive) than previously believed, and can therefore be put under stringent experimental test. To this end, it becomes crucial to compute PV observables of few-nucleon systems starting with the given effective interaction. This constitutes the second aspect of our research. Measurements are available for the following PV observables: the longitudinal analyzing power in $\vec{p}{-}p$ and $\vec{p}{-}\alpha$ scattering, the photon asymmetry and photon circular polarization in, respectively, the ^{1}H$(\vec{n},\gamma)^2$H and ^{1}H$(n,\vec{\gamma})^2$H radiative captures, and the neutron spin rotation in $\vec{n}-\alpha$ scattering. There is also a set of experiments which are currently being planned, including measurements of the neutron spin rotation in $\vec{n}-p$ and $\vec{n}-d$ scattering, and of the longitudinal asymmetry in the charge-exchange reaction ^{3}He$(\vec{n},p))^3$H at cold neutron energies. In Ref. [5] we focussed on this latter observable. At vanishing incident neutron energies, the only channels entering the incoming $n{-}^3$He scattering state have quantum numbers ${}^{2S+1}L_J = {}^1\mathrm{S}_0$ and ${}^3\mathrm{S}_1$. In the out-going $p{-}^3$H scattering state, the relevant channels are ${}^1\mathrm{S}_0$, ${}^3\mathrm{S}_1$, ${}^3\mathrm{D}_1$ with positive parity, and ${}^3\mathrm{P}_0$, ${}^1\mathrm{P}_1$, ${}^3\mathrm{P}_1$ with negative parity. The PV longitudinal analyzing power A_z, reads

$$A_z = a_z \cos\theta, \tag{2}$$

where θ is the angle between the proton momentum and the neutron beam direction, and the coefficient a_z can be expressed in terms of products of T-matrix elements involving parity-conserving (PC) and PV transitions. The latter (related to the real R-matrix elements) for the PC transitions are calculated via the Kohn variational principle with the hyperspherical harmonics method, using strong-interaction Hamiltonian models consisting of the Argonne v_{18} or chiral N3LO two-nucleon potential in combination with the Urbana IX or chiral N2LO three-nucleon potentials. The R-matrix elements involving PV transitions are computed in first-order perturbation theory with Quantum Monte Carlo techniques. The adopted models of the PV interaction have been the DDH potential and the one given by the pionless effective-field-theory (EFT), which only consists of the five contact terms mentioned earlier. As a result of the calculation, the coefficients I_n^{DDH} or I_n^{EFT} are given, such that the asymmetry coefficient a_z is expressed as

$$a_z = \sum_n c_n^\alpha I_n^\alpha, \tag{3}$$

where the superscript α stands for the DDH or EFT model and c_n^α are the strength parameters (coupling constants or combinations thereof) of the corresponding interaction (for the EFT n ranges from 1 to 5). If the parameters entering the DDH potential are varied over their respective allowed ranges, the asymmetry coefficient a_z changes from -27×10^{-8} to $+13 \times 10^{-8}$, which could potentially make its measurement relatively easy. As for the EFT results, no real prediction can be made yet, since a systematic program for the determination of the low-energy constants (LECs) is yet to be carried out. Of course the I_n^{EFT}'s will depend significantly on the value of the momentum cutoff Λ used in the Fourier transform from the momentum space PV potential. In the pionless EFT setting of Ref. [5] Λ has been taken of the order of the pion mass. The analysis could be improved and made fully consistent by employing chiral potentials in both the strong- and weak-interaction sectors. According to our initial remarks, at the 1-loop order of the pionful EFT, the PV potential contains, beside the five LECs associated to the contact terms, only one additional LEC, characterizing the long range one-pion exchange component. When electromagnetic interactions are also introduced, another unknown LEC must be included, characterizing the strength of a PV two-body current operator of pion range. The final aim of the research program is therefore to envisage a suite of experiments involving $A = 2-5$ systems which would allow to determine these seven LECs, and put the HPV on a solid theoretical and phenomenological ground.

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[1] The latter can be imposed, in a non-relativistic theory such as the one involving nucleons, order by order in the low-energy expansion.