Development of a realistic NN potential in Δ-full chiral effective field theory

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The modern understanding of the nuclear interaction is based on the effective field theory framework, which allows to make contact with the underlying dynamics implied by quantum chromodynamics (QCD). Indeed, while the difficulties due to the non-perturbative character of QCD in the domain of nuclear physics prevent, at present, to address this issue from first principles (e.g. on the lattice), many constraints implied by QCD may be consistently accounted for within a well defined perturbative scheme. This is due to the (approximate) chiral symmetry of QCD and to its dynamical breaking. Pions, as Goldstone bosons of this breaking, are the lightest among the hadrons, with a mass mainly due to tiny explicit symmetry breaking terms from light quark masses, and their interactions are weak, as dictated by soft-pion theorems. These two circumstances allow to establish a systematic expansion scheme in powers of small momenta and/or quark masses divided by a hadronic scale $\Lambda_{\rm H}$ ~1 GeV representing the mass of the lightest hadrons whose mass is not protected by chiral symmetry. The predictive power of the effective theory of interacting pions (chiral perturbation theory) is granted by the separation of scales $M_\pi \ll \Lambda_{\rm H}$. Nucleon-nucleon interactions have been developed within this scheme up to the fifth order of the low-energy epansion (usually denoted N4LO) [1,2]. The NN potential is expressed in terms of multi-pion exchanges and a number of contact interaction vertices, which encode the dynamics at short distance and depend on a corresponding set of low-energy constants (LECs), unconstrained by chiral symmetry, to be fitted to experimental data. Their number increases with the order of the expansion. Whether the order-by-order improvement in the accuracy is due to such increasing number of fit parameters or else to the convergence properties of the expansion scheme has to be checked by actual calculations. Such a study has been performed in [2], where it was shown that the convergence pattern in the NN system follows indeed naive expectations based on the power counting. Still, it may be asked whether the explicit inclusion of the Δ resonance in the effective theory is needed or not: the Δ mass is not much separated from the nucleon mass, their difference being actually comparable to the pion mass. Including the Δ explicitly could expand the domain of energy in which the effective theory is applicable, and improve the convergence properties of the expansion. The practical motivation to further refining the NN potential (which, as a matter of fact, may be considered realistic already at N3LO), comes from the study of 3-nucleon systems, where the convergence pattern up to N3LO is not as satisfactory as for the NN system.

In Ref. [3] we constructed a NN potential in chiral effective field theory up to N3LO, including the Δ explicitly. The potential also includes an electromagnetic interaction component, including up to terms quadratic in the fine structure constant α (first- and second-order Coulomb, Darwin-Foldy, vacuum polarization, and magnetic moment interactions), which is the same as the one adopted in the phenomenological Argonne V18 potential [4]. The long-range part of the interaction is given by one-pion exchange (OPE) and twi-pion exchange (TPE) contributions, illustrated in Fig. 1. Coordinate-space expressions, which are singular at the origin, are regularized by a local long-distance cutoff $R_L = (0.8, 1.0, 1.2)$ fm. The short distance component of the strong interaction, includes isospin-symmetric interactions at LO, NLO and N3LO, and isospin-violating ones at LO and NLO. They depend respectively on 2, 7 and 15 LECs for the isospin-symmetric contributions and on 2 and 8 LECs for the isospin-violating ones. Making use of Fierz rearrangements, these interactions have

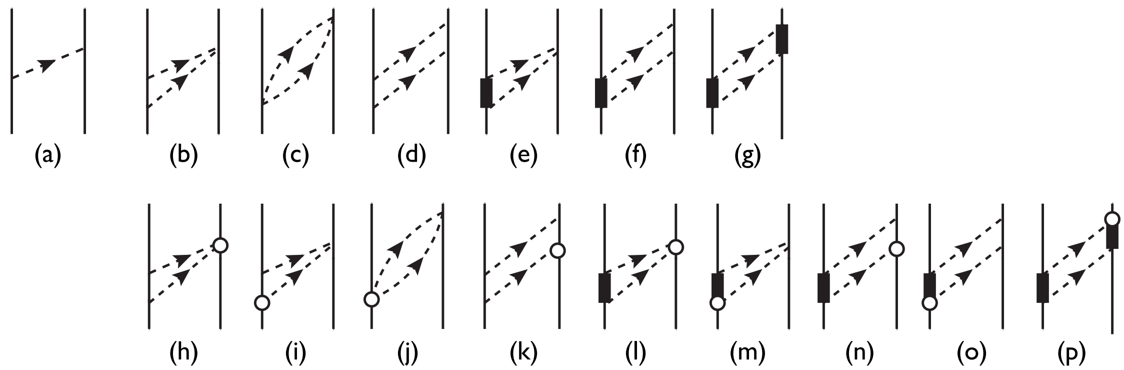

Figure 1. One- and two-pion exchange contributions at LO (a), NLO (b)(g), and N2LO (h)(p). Nucleons, isobars, and pions are denoted, respectively, by the solid, thick solid, and dashed lines; both direct and crossed box contributions are retained in diagrams (d), (f)(g), (k), and (n)(p). The open circles denote πN and $\pi N\Delta$ couplings from the subleading chiral Lagrangians. Relativistic $1/M_N$ corrections (M_N is the nucleon mass) included in the subleading πN Lagrangian are not considered here. In particular the contributions of diagrams (i), (k), and (n) are neglected.

been written so as to provide a minimally nonlocal interaction in coordinate space. This feature offers many computational advantages for ab-initio calculations of nuclear structure and reactions, in particular for the type of quantum Monte Carlo calculations of $s-$ and $p-$ shell nuclei. A delicate point in the development of realistic NN potentials is the experimental data used in the fit. There are currently about 8000 published pp and np scattering data below pion production threshold, corresponding to 24 different scattering observables, including differential cross sections, spin asymmetries, and total cross sections. Unfortunately, not all of them are mutually compatible and a selection has to be made. We adopted the Granada database [5], which is based on the adoption of a general and flexible parametrization to obtain a 3σ self-consistent set of data, by removing the outliers and re-fitting iteratively until convergence. We constrained the short-distance LECs by fitting to these pp and np scattering data (including normalizations) up to 300 MeV laboratory energies and the pp, np, and nn scattering lengths and deuteron binding energy, using the derivative-free POUNDerS algorithm [6]. For three different adopted models, characterized by different choices of short-distance cutoffs of the order of the two-pion range, we find χ^2/datum = 1.48, 1.48, 1.52 for pp data and χ^2/datum=1.20, 1.19, 1.23 for np data, corresponding to a global chi^2/datum=1.33, 1.33, 1.37. Errors for the pp data are significantly smaller than for np, which results in a larger χ^2. For comparison we note that the Entem and Machleidt N3LO fit up 290 MeV laboratory energy produces a χ^2/datum =1.1 for 2402 np data and 1.5 for 2057 pp data [7], while the AV18 χ^2 to the same database as ours is 1.46. It is also important to stress that the fitting to experimental observables rather than to partial wave analyses is the only way to enable to draw firm conclusions in regard to the statistical significance of, e.g., the order-by-order convergence of the chiral expansion.

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