Chiral dynamics in few–nucleon systems

E. Epelbaum* (for the BJC Collaboration)†
Forschungszentrum Jülich, Institut für Kernphysik (Th), D-52425 Jülich, Germany

Chiral effective field theory offers a systematic and controlled method to study the dynamics of few–nucleon systems. In the approach proposed by Weinberg, one starts from an effective Lagrangian of nucleon and pion fields as well as external sources, in harmony with chiral and gauge invariance. Based on a systematic power counting, one constructs a potential, which is further subjected to a unitary transformation to avoid any energy-dependence [1]. To leading order, one has the one–pion exchange together with two four–nucleon interaction terms accompanied by low–energy constants (LECs). At next–to–leading order, renormalizations of the OPE, the leading two–pion exchange diagrams and seven more 4N operators appear. At NNLO, we have in addition dimension two pion–nucleon operators, whose LECs can be determined from the chiral analysis of πN scattering. This serves as the link to the chiral QCD dynamics. The potential is then used in a properly regularized Lippmann–Schwinger equation (e.g. by a sharp or exponential momentum cut-off) to generate the bound and scattering states, as detailed in ref.[2]. The iteration of the potential leads to a non–perturbative treatment of the pion exchange which is of major importance to properly describe the NN tensor force. The nine LECs can be determined from a fit to the low np partial waves, e.g. the description of the S-waves is as good as in any partial wave analysis up to pion production threshold. Most other partial waves are also well reproduced, with some exceptions in the D– and F–waves. Most static deuteron properties are also well described without any fine tuning. It should be noted that in this approach one encounters deeply lying bound states at NNLO, which have no influence on the low energy dynamics. In the same framework, one can also include charge symmetry breaking and charge dependence of the nuclera force by including the light quark mass difference and elecromagnetic corrections [3]. Phase shifts for pp and nn scattering can be compared to what is obtained using the Nijmegen, Argonne or CD-Bonn potentials. Elastic electron–deuteron scattering has also been investigated to NNLO [4], leading to a good description of the deuteron form factors and structure function up to photon virtualities of 0.2 GeV^2, which is largely limited by the single nucleon form factors in the impulse terms. The extension to three– and four–nucleon systems has also been started using the NLO potential, see [5]. At this order, no 3N forces appear and one can make parameter–free predictions. The results for binding energies and scattering/break-up processes are comparable in precision to the ones based on modern phenomenological potentials like e.g. CD-Bonn. In addition, first NNLO results including only two–nucleon forces will be presented. A new approach to construct the EFT potential without deeply bound states will be presented, it is based on the observation that in microscopic models of the NN forces TPE contributions are largely cancelled by $\pi\rho$ exchange diagrams. This can be modeled in EFT by subtracting the delta contribution from the dimension two πN LECs c_3, c_4 [6,7]. The so constructed NNLO potential can be directly compared to the high-precision ones. It can be shown that the numerical values of the LECs can be understood on the basis of phenomenological one–boson–exchange models [6]. We also extract these values from various modern high accuracy nucleon–nucleon potentials and demonstrate their consistency and remarkable agreement with the values in the chiral effective field theory approach. This paves the way for estimating the low–energy constants of operators with more nucleon fields and/or external probes. Furthermore, it can be demonstrated that the highly singular chiral EFT potential exhibits a so–called limit cycle behaviour in the limit of letting the cut–off go to infinity [8]. This allows to regulate the troublesome D– and F–waves. A further outlook and discussion of outstanding problems will also ge given.

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*Email: Evgeni.Epelbaum@tp2.ruhr-uni-bochum.de
†Bochum–Jülich–Cracow Coll.: EE, W. Glöckle, Ulf-G.Meißner, H. Kamada, A. Nogga, H. Witala, M. Walzl.