Electromagnetic structure and reactions of few-nucleon systems in χEFT

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Chiral effective field theory (χEFT), as a tool to describe the nuclear interaction, has by now reached a comparable level of accuracy to the most realistic phenomenological potentials. The perturbative series for the nucleon-nucleon (NN) interaction has been pushed to the next-to-next-to-next-to leading order (N3LO), with a resulting χ^2 per datum very close to 1. The χEFT formalism also allows to describe the interaction of electroweak probes with nuclei at low energies. Therefore, it becomes possible to describe electroweak processes in few-nucleon systems in a fully consistent way, with potentials and currents derived within the same formalism. This is a significant conceptual advance with respect to the so called hybrid approach: in the latter, the chiral expansion is applied to the transition operator, while the nuclear states, in which to take matrix elements, are generated by phenomenological realistic potentials. In Ref. [1] we construct consistently within the χEFT framework, a NN potential and one- and two-body electromagnetic currents up to N3LO, with the ultimate aim of studying electromagnetic properties and radiative captures in few-nucleon systems at this order. The calculation is performed within the framework of time-ordered perturbation theory, in order to clearly disentangle two-nucleon reducible and irreducible contributions: the former have to be discarded since they are generated by the iteration of the dynamical (Lippman-Schwinger) equation. In this respect, particular care has to be taken in the treatment of recoil corrections to the reducible diagrams, since they produce subtle partial cancellations of the irreducible ones. Loop diagrams are handled in dimensional regularization and the renormalization program is consistently applied. The nine low-energy constants (LECs) which enter the potential at this order are determined by fitting the np S- and P-wave phase shifts up to 100 MeV lab energies of the most recent partial wave analysis. The electromagnetic current operator starts at leading order (LO) with the coupling of the external photon field to the individual nucleons. NLO terms involve seagull and pion-in-flight contributions associated with one-pion exchange, and the N2LO terms represent relativistic corrections to the LO one-body current. At N3LO the current consists of different type of contributions: *i*) currents generated by minimal substitution in the two-nucleon contact interactions involving two gradients of the nucleons' field, as well as by non-minimal couplings; *ii*) one-pion-exchange contributions involving the standard πNN vertex on one nucleon and a subleading $\gamma\pi NN$ vertex on the other nucleon; *iii*) two-pion exchange currents at one loop; *iv*) one-loop corrections to tree-level currents; and *v*) relativistic corrections to the NLO currents resulting from the non-relativistic reduction of the vertices, which we neglect for the time being[1]. We also observe that no three-body currents arise at this order of the chiral expansion. The LECs associated with the minimal coupling contact terms are fixed from the fit of the NN potential. There are two independent non-minimal coupling contact operators at this order, and the corresponding LECs are to be considered as free parameters. As for contributions of type *ii*), the associated LECs, could be in principle determined by pion photoproduction data on a single nucleon, or by resonance saturation arguments, or else they could be considered as free parameters, to be fitted to nuclear data. The stage is now set for carrying out a consistent χEFT calculation of electromagnetic properties and reactions

[1]Such kind of relativistic corrections are not implemented in the available "realistic" chiral potentials.

in $A = 2-4$ nuclei. In Ref. [2] we use the obtained expressions of the electromagnetic current to study the nd and $n\,{}^3$He radiative captures at thermal neutron energies. In these reactions the magnetic dipole transitions connecting the continuum states to the hydrogen and helium bound states are inhibited at the one-body level. Hence, most of the calculated cross sections results from contributions of many-body components in the electromagnetic current operator, and are therefore an ideal testing ground for our χEFT setting. The calculations are carried out by evaluating the matrix elements of these operators between wave functions obtained from either conventional (e.g. AV18) or chiral (N3LO) realistic potentials with the variational hyperspherical harmonics method. The NN potentials are used in combination with the Urbana IX and chiral N2LO three-nucleon interactions. One combination of the five LECs is fixed from Δ resonance saturation, while the other LECs are determined from nuclear data, specifically the experimental np cross section and magnetic moments of the deuteron and trinucleons (cfr. Fig. 1). The bands represent the spread in the calculated values corresponding to the two Hamiltonian models considered here. The dependence on the cutoff (varied between 500 and 700 MeV) remains quite weak for these observables. Having fully constrained the χEFT $M1$ operator up to N3LO, it is then possible to provide predictions for the nd and $n\,{}^3$He radiative capture cross sections, denotes as σ^γ_{nd} and $\sigma^\gamma_{n\,^3\mathrm{He}}$, and the photon circular polarization parameter R_c resulting from the capture of polarized neutrons on deuterons. These are shown in Fig. 2, confronted with experimental data (large black bands). The predicted cross sections are in good agreement with data, but exhibit a significant dependence on the input Hamiltonian. It can also immediately be seen that the LECs contributions are large, and essential for bringing theory into good agreement with experiment. Indeed, the convergence of the chiral expansion is problematic for these processes. The LO is unnaturally small, as already remarked, leading to an enhancement of the NLO, which, however, in the case of $n\,{}^3$He is offset by the destructive (and accidental) interference between it and the LO contribution. It is likely that explicit inclusion of Δ degrees of freedom will significantly improve the convergence pattern.

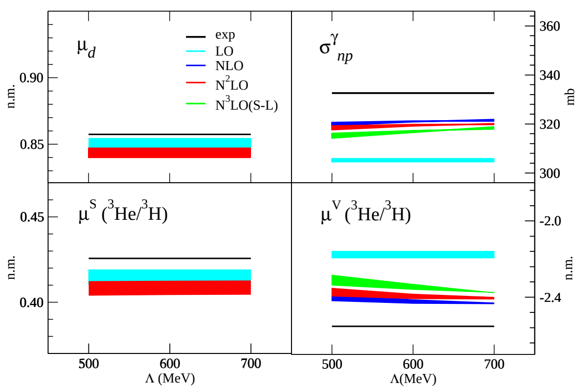

Figure 1. Results for the deuteron and trinucleon isoscalar and isovector magnetic moments, and np radiative capture, obtained by including cumulatively the LO, NLO, N2LO and N3LO (S-L) (i.e. without LECs) contributions.

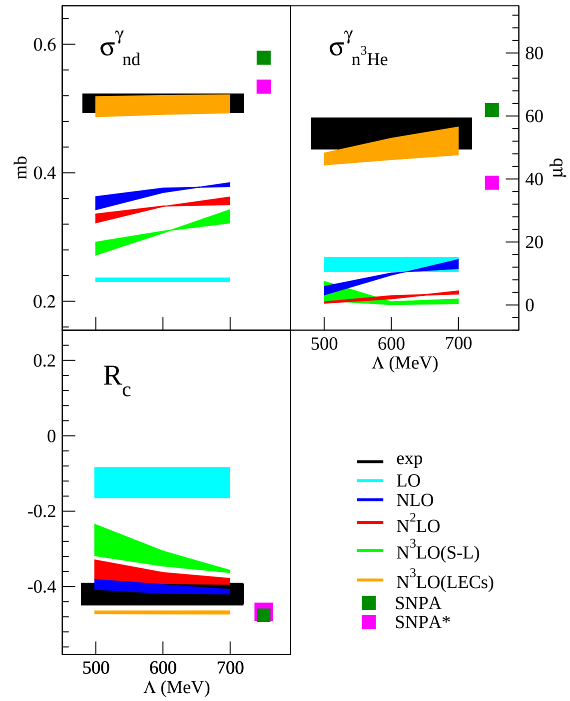

Figure 2. Results for σ^γ_{nd}, $\sigma^\gamma_{n\,^3\mathrm{He}}$ and R_c obtained by including cumulatively the LO, NLO, N2LO, N3LO (S-L) and N3LO (with LECs) contributions. Also shown are predictions obtained in the standard nuclear physics approach (squares labeled SNPA and SNPA*, the latter retaining the relativistic corrections to the one-body current), in which the current operator includes two- and three-body terms so as to satisfy exactly current conservation with the two- and three-nucleon potentials AV18 and Urbana IX.

REFERENCES

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