Electromagnetic structure of light nuclei in Chiral Effective Theory

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Besides providing a justification for the hierarchy of nuclear forces, establishing a clear contact with the underlying theory of strong interaction and its symmetries, and leading to a well defined expansion scheme, susceptible of systematic improvement, the chiral effective field theory (χEFT) is ideally suited for deriving consistent electroweak currents. Indeed, chiral perturbation theory is formulated as an effective theory of external currents, which are coupled to the degrees of freedom of the fundamental theory. The constraints imposed by chiral symmetry, so-called chiral Ward identities, are obtained promoting the global chiral symmetry to a local one [1], with the external currents r_μ and ℓ_μ, representing the corresponding gauge fields. The explicit breaking of chiral symmetry by quark masses and electromagnetic currents is naturally implemented: correlation functions are to be evaluated with the scalar source χ proportional to the quark mass matrix and the external currents set equal to the photon field, $r_\mu = \ell_\mu = QA_\mu$ with $Q = e\,\mathrm{diag}(\frac{2}{3}, -\frac{1}{3})$ in the meson sector and $Q = e\,\mathrm{diag}(1, 0)$ in the nucleon sector.

The effective Lagrangian is the most general one invariant under chiral symmetry: it contains an infinite number of operators, classified according to the chiral counting, a combined expansion in powers of quark masses and small momenta, with $\chi \sim O(p^2)$. The chiral counting is thus the organizing principle: it works because Goldstone bosons have derivative interactions, as dictated by the Goldstone's theorem.

A generic transition amplitude can be obtained from the interaction Hamiltonians in the framework of time-ordered perturbation theory. This allows to isolate the so-called reducible diagrams, i.e. those that contain purely nucleonic intermediate states. Indeed such diagrams are enhanced by the presence of small energy denominators, and need to be resummed to all orders. This is accomplished by the dynamical equations (e.g. the Lippman-Schwinger equation), whose kernel admits a well defined low-energy expansion. The predictions for physical observables are parametrized, at each order, by a finite set of universal constants, so-called low-energy constants (LECs), which have to be taken from other experiments, and effectively implement the relations that chiral Ward identities impose on different observables. The divergent loop integrations are regularized with a cutoff Λ. The Λ dependence should be absorbed by the running of the LECs, would all orders be considered at once. Thus the remaining Λ dependence signals the convergence of the expansion scheme.

Within this framework we have calculated the nuclear electromagnetic current [2] and charge [3] operators up to one-loop order of the chiral expansion, amounting respectively to (next-to-)^{3}leading order (N3LO) and N4LO, and obtained reasonable predictions for thermal neutron captures on deuteron and ^{3}He [4], although the convergence pattern was not entirely satisfactory. More recently, in Ref. [5] we have devised a further scheme for the extraction of the relevant LECs, which leads to stable results, and calculated the resulting electric and magnetic form factors of deuterons and trinucleons. There are 5 LECs which enter the nuclear electromagnetic current operator up to one loop order, while the charge operator is parameter-free. Two of the unknown LECs (one isoscalar and one isovector) are genuinely two-nucleon parameters, entering the two-nucleon contact Lagrangian. The remaining three come from the subleading pion-nucleon Lagrangian, and they are in principle measurable in pion-nucleon processes. However, the large uncertainties associated with such procedure, motivate us to use nuclear data to constrain them.

In addition we use Δ-resonance saturation to fix two of the isovector LECs, and therefore we are left with one additional isoscalar LEC. We fix the two isoscalar LECs, denoted d_1^S and d_2^S, to reproduce the deuteron magnetic moment and the isoscalar combination of the trinucleon magnetic moments. This is done for different values of Λ and for different models of two- and three-nucleon interaction, namely AV18+UrbanaIX and chiral N3LO+N2LO potentials. In order to fix the isovector LEC, we use either the isovector combination of the trinucleon magnetic moments or the neutron-proton capture cross sections, as displayed in Fig. 1. As it is apparent, we obtain

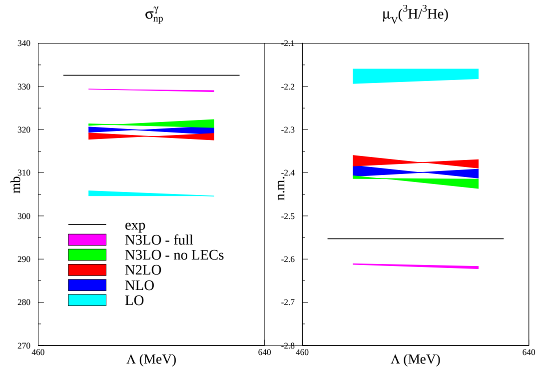

Figure 1. Cumulative contributions to the isovector combination of the trinucleon magnetic moments and to the neutron-proton capture cross section, using either of the two observables to fix the isovector LEC.

stable, model-independent predictions to 1% and 2% respectively. With all the LECs determined, we derive predictions for the electric charge and quadrupole form factor and magnetic form factors of deuteron and trinucleons. The results for the magnetic form factors are compared to the experimental data in Figg. 2 and 3. The deuteron electromagnetic structure is perfectly described up to momentum transfers of 2-3 fm^{-1}, and actually for the charge form factor this agreement extends to much larger momenta $\sim$ 6 fm^{-1}, certainly larger than the range of validity of the chiral expansion. Curiously, the hybrid calculation (with AV18 potential) exhibits a much weaker cutoff dependence, and this signals a significant scheme dependence. Also for the $A = 3$ nuclei we obtain a good description up to $q \sim 3$ fm^{-1}, with a large effect of two-body currents, while the data are underpredicted at higher momenta. Also for the charge form factor we obtain similar behaviour, with the chiral loops decisive in bringing theory closer to the data in the diffraction region.

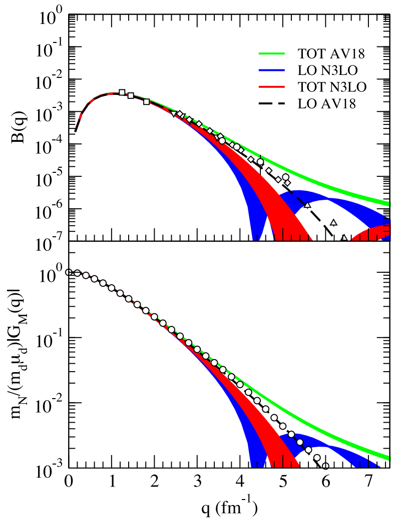

Figure 2. Deuteron $B(q)$ structure function and magnetic form factor compared with the result at leading order (LO) and with experimental data, for the two adopted interaction models. The bands denote the variation with Λ.

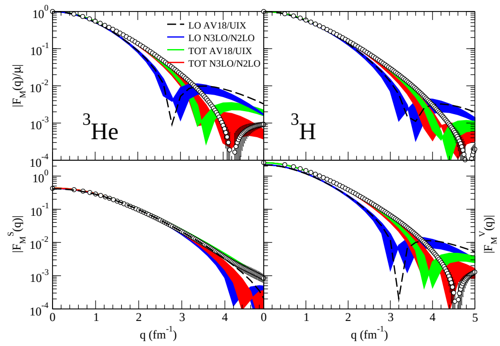

Figure 3. ^{3}He and ^{3}H magnetic form factors and their isoscalar/isovector combinations. Notations as in Fig. 2. The isovector LECs is fixed to the magnetic moment.

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