Tritium β decay in chiral effective field theory

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The derivation of hadronic physics from the underlying theory of quantum chromodynamics (QCD) remains an open issue of current research in particle physics. Indeed hadrons are a rather indirect manifestation of QCD, and most of what we know relies on symmetry properties, that put constraints on hadrons and their interactions. Besides generic constraints such as Poincaré, parity, time-reversal symmetry, there are stringent constraints more specifically related to QCD and its symmetries, namely the (approximate) chiral symmetry and its dynamical breakdown, which in turns can be shown to be a consequence of color confinement. As a result, we have (approximately) conserved vector and axial Noether currents, that satisfy the chiral Ward identities. The phenomenological relevance of this observation is due, on one hand, to the fact that Noether currents correspond to physical currents, coupled to weakly interacting particles; therefore, their matrix elements enter in processes involving these particles, like electron scattering, weak captures, β decays, etc. On the other hand, the dynamical chiral symmetry breakdown allows to establish a systematic calculational scheme for low-energy observables, based on a perturbative expansion in powers of momenta or pion masses, divided by the typical hadronic scale $\Lambda_{\rm H} \sim 1$ GeV, since the pions, as Goldstone bosons, are light and interact weakly at low energy. Of course there is no warranty about the convergence of such an expansion. In particular, one should expect a slower convergence if the mass scales are not well separated.

This framework, which is known as chiral effective field theory (ChEFT), has provided a mean to derive nuclear interactions and electroweak charge and current operators, since the first proposal made by Weinberg in the last decade of the last century. In Ref. [1] we have calculated the nuclear two-body axial charge and current operators up to the fourth order of the low-energy expansion, i.e. including two-body 1-loop corrections, within the scheme that was adopted in the past for the case of the nuclear electromagnetic charge and current operators [2], based on time-ordered perturbation theory. For an analogous calculation within another scheme, so-called unitary-transformation method, see Ref. [3]. In Ref. [4] we use the so-derived nuclear axial current operator to evaluate the Gamow-Teller matrix elements of tritium β decay. In a three-nucleon the two-body loop corrections to the axial current enter at the same order as the three-body axial current, illustrated in Fig. 1. They do not entail any new low-energy constant (LEC). The only LEC that the axial current depends on is z_0, driving a two-body contact current, that we fit to the experimental Gamow-Teller matrix element. These matrix elements are calculated with Quantum Monte Carlo techniques using ^{3}H and ^{3}He wave functions obtained with the hyperspherical harmonics expansion method from two- and three-nucleon potentials derived from either ChEFT (for two values of the cutoff, $\Lambda = 500$, 600 MeV) or the phenomenological approach (the Argonne V18 in combination with Urbana IX).

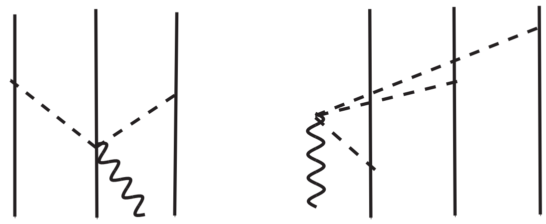

Figure 1. Diagrams illustrating the three-body axial current at N4LO. Nucleons, pions and axial fields are denoted by solid, dashed and wavy lines, respectively. Only a single time ordering is shown and pion-pole contributions are ignored.

We show in Fig. 2 the cumulative contributions

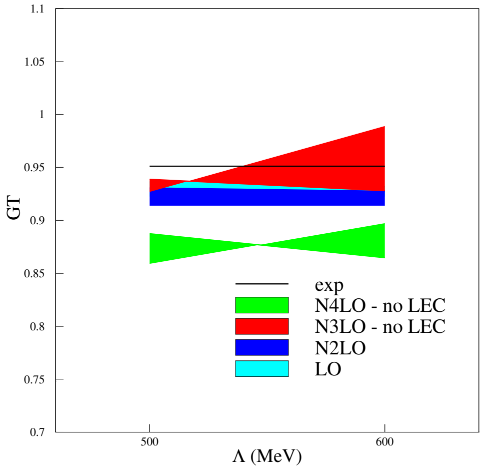

Figure 2. Cumulative contributions to the Gamow-Teller matrix element of tritium β decay, from leading order (LO) to N4LO. The contributing LEC (which enters at N3LO) is not included, as it is fitted to reproduce the experimental value (black line). The band reflect the dependence on the cutoff (for the interactions derived in ChEFT) and on the model (we used the Argonne V18).

to the Gamow-Teller matri element of tritium β decay. The bands indicate the model and cutoff-dependence. It is clear that the convergence pattern doesn't look satisfactory. In particular the role of the LEC seems more important than contributions arising at previous orders of the expansion. And the resulting value of the LEC changes considerably from N3LO to N4LO. These observations are also illustrated in Fig. 3, in which the truncated expansions of the matrix elements (as determined at N4LO) are displayed. The error bars denote the expected size of the theoretical uncertainty, as determined by naive dimensional analysis. A well-behaved series would exhibit at a given order a result within the error bars of the previous one. This is obviously not the case. The bottom panel of the same figure shows the same quantity, but with the LEC z_0 nominally promoted by two orders in the perturbative series. Promotions of contact terms of this kind have been repeatedly proposed in the literature, (see e.g. [5]) based on renormalization group arguments. We see that in this latter case the series is much better behaved.

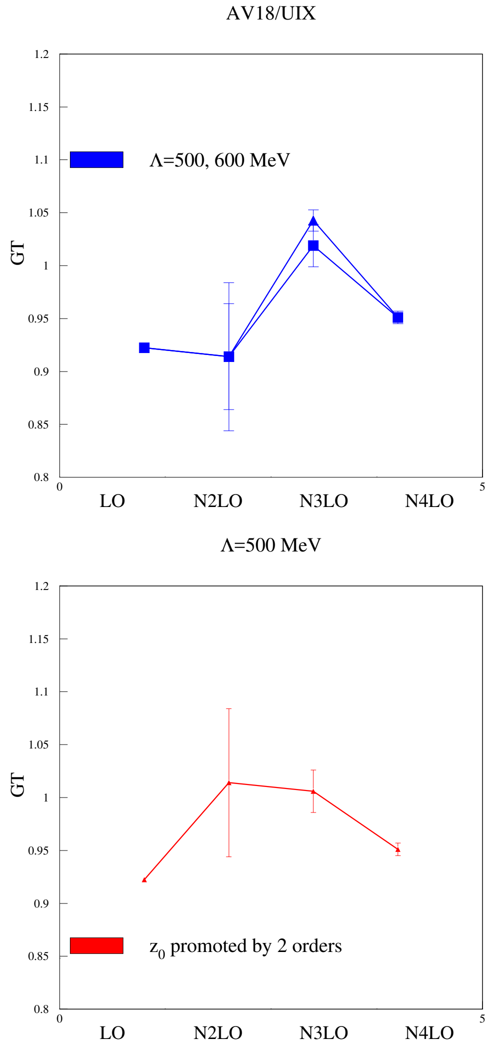

Figure 3. Convergence pattern of the Gamow-Teller matrix element as a function of the perturbative order, in the case of ordinary power counting (top panel), or after promotion of the contact current (bottom panel).

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