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Electroweak Currents from Chiral Effective Field Theory

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Abstract Since the pioneering work of Weinberg, Chiral Effective Field Theory (χEFT) has been widely and successfully utilized in nuclear physics to study many-nucleon interactions and associated electroweak currents. Nuclear χEFT has now developed into an intense field of research and is applied to study light to medium mass nuclei. In this contribution, we focus on the development of electroweak currents from χEFT and present applications to selected nuclear electroweak observables.

A major objective of nuclear theory is to explain the structure and dynamics of nuclei and their interaction with electroweak probes in a fully microscopic approach. In such an approach, nucleons interact with each other via many-body (primarily, two-and three-nucleon) interactions, and with external electroweak probes, such as electrons, neutrinos, and photons, via many-body currents describing the couplings of these probes to individual nucleons and many-body clusters of correlated nucleons. Over the past sixty years, several highly accurate phenomenological interactions [1,2] have been developed and successfully applied to study nuclear properties. Despite this success, phenomenological theories are hardly improvable; moreover, their connection to the underlying theory ultimately governing nuclear dynamics, that is Quantum Chromodynamics (QCD), is ambiguous. Chiral effective field theory (χEFT), formulated by Weinberg in the Nineties [3–5], resolves these shortcomings.

χEFT is a low-energy approximation of QCD whose degrees of freedom are bound states of QCD (e.g., pions, protons, neutrons, etc.). It exploits the symmetries exhibited by QCD in the low-energy regime, in particular chiral symmetry, to constrain and determine the interactions of pions among themselves and with other baryons. The pion couples to these particles by powers of its momentum \( Q \) and mass, and the Lagrangians describing these interactions can be expanded in powers of \( Q/\Lambda \), where \( \Lambda \sim 1 \text{ GeV} \) represents the chiral-symmetry breaking scale and characterizes the convergence of the expansion. Therefore, the validity of the theory is confined to kinematic regions where the constraint \( Q \ll \Lambda \) is realized. The coefficients of the chiral expansion, or low-energy constants (LECs), are unknown and need to be fixed by comparison with experimental data or calculated by nonperturbative QCD computational methods such as Lattice QCD [7–17].

This extremely powerful approach provides an expansion of the Lagrangians in powers of a small momentum as opposed to an expansion in the strong coupling constant, restoring de facto the applicability of pertur...
bative techniques also in the low-energy regime. Due to the chiral expansion it is then possible, in principle, to evaluate an observable to any degree of desired accuracy and to know *a priori* the hierarchy of interactions contributing to the (low-energy) process under study. The systematic expansion in $Q/\Lambda$ naturally arranges the operators in increasing numbers of nucleons. For example, in the $Q/\Lambda$ power counting, three-nucleon forces are suppressed with respect to two-nucleon forces, and so on. Another crucial feature of $\chi$EFT is that many-body electroweak currents can be readily and consistently constructed within the same $\chi$EFT adopted to derive the many-nucleon interactions.

Since the pioneering work of Weinberg [3–5], this calculational scheme has been widely utilized in nuclear physics [6,18–61] and nuclear $\chi$EFT has developed into an intense field of research. In this contribution, we focus on the development of electroweak currents from $\chi$EFT [6,42–58] and present applications to selected observables in light and medium mass nuclei [62–69].

Nuclear electroweak current ($j$) and charge ($\rho$) operators can be expressed as a sum of one and many-body contributions, namely

$$\rho(q) = \sum_i \rho_i(q) + \sum_{i<j} \rho_{ij}(q) + \cdots,$$

$$j(q) = \sum_i j_i(q) + \sum_{i<j} j_{ij}(q) + \cdots,$$

where $q$ is the momentum carried from the external field and the dots denote three-body operators and beyond. To illustrate the kind of currents emerging from a $\chi$EFT with pions, nucleons, and delta excitations, in Fig. 1 we show the vector axial current at tree-level up to next-to-next-to-next-to-leading order (N3LO), corresponding to chiral order $Q^0$, at zero momentum transfer. The major contribution is from the leading order single-nucleon operator (panel a), this corresponds to the standard Gamow-Teller operator. Two-body corrections enter at N2LO (chiral order $Q^{-1}$) with a transition current where a nucleon is excited into a delta, which decays into a pion that gets reabsorbed by a second nucleon (panel c). At N3LO, there is another one-pion range two-body current (panel d), along with a contact current (panel e). Because of the power counting, kinematic effects can also be accounted for and arranged within the power expansion. A term of this kind is illustrated in panel b, representing a relativistic correction to the leading one-body operator. All the LECs entering these operators are experimentally known except for that entering the contact term in panel e, which is determined by fits to experimental data [70].

The pioneering derivations of both vector and axial vector currents up to one-loop contributions are from Park, Min and Rho [41,42] who worked within an heavy-baryon formulation of chiral perturbation theory.

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Fig. 1 Diagrams illustrating the contributions to the axial current up to N3LO at zero momentum transfer. Nucleons, deltas, pions, and external weak fields are denoted by solid, thick-solid, dashed, and wavy lines, respectively. The square in panel b represents relativistic corrections, while the dot in panels d denotes a vertex induced by subleading terms in the $\pi$-nucleon chiral Lagrangian [6].
with pions and nucleons as degrees of freedom. These currents, have been used by Song and collaborators in several hybrid calculations in $A \lesssim 3$ nuclei [59,60]. The electromagnetic charge operator was first investigated within $\chi$EFT by Walzl et al. in Ref. [48] and Phillips in Refs. [45–47]. More recently, derivations based on two different implementations of time-ordered perturbation theory appeared in the literature. One is from the so-called Pisa-JLab group [49–52] and the other is from the Bochum-Bonn group [53,54,77,78]. The latter is based on the method of the unitary transformation [79] that decouples, in the Hilbert space of pions and nucleons, states consisting of nucleons only from those including both pions and nucleons. The two derivations differ in the treatment of reducible diagrams [50,54,55,70]. When calculating box diagrams entering the electromagnetic charge and current operators [51,56], the two methods lead to results that are in agreement. However, as discussed at length in Refs. [56,70], the two groups find different results for the box diagrams in the loop contributions to the axial current operator. The (minor) numerical impact of this difference has been investigated in Ref. [70]. Further checks are underway to clarify the origin of these differences [80]. Both formulations, have been used in calculations of electroweak observables in (primarily) light nuclei.

In Fig. 2, we show calculations of the deuteron magnetic form factor based on $\chi$EFT currents calculated by Kölling et al. in Ref. [53] and Piarulli et al. in Ref. [52]. The theoretical results are in very good agreement with each other and with the experimental data for values of momentum transferred $q \lesssim 3$ fm$^{-1}$. $\chi$EFT currents are first used for nuclei with $A > 3$ in Ref. [66] where they are included when studying magnetic moments and electromagnetic transitions in $A \lesssim 10$ systems. Two-body currents always improve on the agreement between experimental data and theoretical calculations. A long standing under-prediction [84] by less sophisticated theoretical estimations of the measured $^9$C magnetic moment is in Ref. [66] explained by the presence of a 40% correction generated by two-body electromagnetic currents. This enhancement can be appreciated in Fig. 3 by comparing blue dots (representing calculations based on the single nucleon paradigm) and red diamonds (representing calculations with two-body electromagnetic currents).
Fig. 4 Ratios of Green’s function Monte Carlo calculations to experimental values of the Gamow-Teller reduced matrix elements in the $^3$H, $^6$He, $^7$Be, $^8$Li, $^8$B, $^8$He and $^{10}$C weak transitions from Refs. [68,69]. Theory predictions correspond to the $\chi$EFT axial current at LO (empty symbols) and up to N3LO (filled symbols).

Fig. 5 Comparison of experimental (y-axis) and theoretical (x-axis) Gamow-Teller matrix elements for medium-mass nuclei. The theoretical results were obtained using (i) a bare Gamow-Teller one-body operator, (ii) Gamow-Teller one-body operator consistently evolved with the Hamiltonian [65], and (iii) a consistently-evolved Gamow-Teller operator that includes both one- and two-body currents. See Ref. [65] for details.
Axial currents are tested primarily in beta decays and electron capture processes for which data are readily available and known for the most part with great accuracy. The long-standing problem of the systematic overprediction of Gamow-Teller beta decay matrix elements \([85]\) in simplified nuclear calculations, the so-called \(g_A\) problem\footnote{E. Epelbaum, H.-W. Hammer, U.-G. Meissner, Modern theory of nuclear forces. Rev. Mod. Phys. \textbf{81}, 1773–1825 (2009)} \footnote{R. Machleidt, D.R. Entem, Chiral effective field theory and nuclear forces. Phys. Rept. \textbf{503}, 1–75 (2011)} \footnote{D.R. Entem, N. Kaiser, R. Machleidt, Y. Nosyk, Peripheral nucleon-nucleon scattering at fifth order of chiral perturbation theory. Phys. Rev. \textbf{C91}(1), 014002 (2015)}\footnote{A. Parreño, P. E. Shanahan, M. L. Wagman, F. Winter, E. Chang, W. Detmold, Two nucleon systems at \(m_\pi \sim 450\text{MeV}\) from lattice QCD. Phys. Rev. D \textbf{92}(11), 114512 (2015) \footnote{K. Orginos, A. Parreno, M.J. Savage, S.R. Beane, E. Chang, W. Detmold, Two nucleon systems at \(m_\pi \sim 450\text{MeV}\) from lattice QCD. Phys. Rev. D \textbf{95}(no.5), 059902 (2017)}} has been recently addressed by several groups \([65,68,69]\). The authors in Refs. \([68,69]\) calculated the Gamow-Teller matrix elements in \(A = 6 \rightarrow 10\) nuclei accounting systematically for many-body effects in nuclear interactions and coupling to the axial current both derived in \(\chi\)EFT. The agreement of the calculations with the data is excellent for \(A = 3, 6\) and 7 systems, with two-body currents providing a small \((\sim 2\%)\) contribution to the matrix elements. Decays in the \(A = 8\) and 10 systems, instead, require further developments of the nuclear wave functions \([65,69]\). The \(g_A\)-problem\footnote{R. Machleidt, The high precision, charge dependent Bonn nucleon-nucleon potential (CD-Bonn). Phys. Rev. C \textbf{63}, 024001 (2001)} can be resolved in light nuclei largely by correlation effects in the nuclear wave functions. A summary of these calculations is reported in Fig. 4. Similar results for these light nuclei obtained using the No-core shell model are reported in Ref. \([65]\).

The \(\chi\)EFT approach in recent year is being implemented in studies of medium mass nuclei \([65]\]. As a representative of this class of electroweak calculations we show the results of Ref. \([65]\) on beta decay matrix elements represented in Fig. 5. Here, the authors demonstrate that the quenching in the nuclear matrix elements arises primarily from \(\chi\)EFT axial two-body currents and strong correlations in the nucleus. Nuclei from \(A = 3\) to \(^{100}\text{Sn}\) are analyzed with \(\chi\)EFT predictions in agreement with experimental data.

There has been exceptional progress in studying nuclear physics using \(\chi\)EFT. In the last two decades, this framework rooted in the symmetries and breaking pattern of QCD has allowed for the calculation of many low-energy nuclear processes, such as electromagnetic reactions and \(\beta\) decays in both light and medium-mass nuclei, has reached a remarkable agreement with experiment, and has contributed to solving long-standing anomalies in nuclear theory. As chiral interactions and currents are being refined and pushed to higher orders, we have entered the precision era of this powerful framework.

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