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Trinucleon Electric Dipole Moments in Chiral EFT

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Time reversal violation (TRV) sources in fundamental theories induce interactions between nucleons which can be revealed by looking at the presence of permanent electric dipole moments (EDM) of light nuclei. By using the chiral effective filed theory (χEFT) it is possible to connect the nuclear observables to the fundamental terms which induce TRV. In this work we derive the TRV nucleon-nucleon and three-nucleon potential up to next-to-next-to leading order (N2LO) by using χEFT. The TRV interaction is then used to evaluate the EDM of ^{3}H and ^{3}He focusing in particular on the calculation of the theoretical errors and the convergence of the chiral expansion.

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1. Introduction

Time Reversal Violation (TRV) and Parity Violation (PV) are key ingredients in the explanation of the observed baryon-antibaryon asymmetry in the Universe (BAU) [1]. The Standard Model (SM) has a natural source of CP-violation in the Cabibbo-Kobayashi- Maskawa (CKM) quark mixing matrix, however this mechanism is not sufficient to explain the observed value of BAU [2]. This discrepancy opens a window in possible TRV effect in extension of SM, such as the θ-term in the Quantum Chromodynamics (QCD) sector [3], or in beyond-SM (BSM) theories [4].

The measurement of Electric Dipole Moments (EDMs) of particles is the most promising observable for studying TRV effects beyond CKM mixing matrix. The present experimental upper bounds on the EDMs are $|d_n| < 2.9 \cdot 10^{-13}$ e fm for neutron [5], $|d_p| < 7.9 \cdot 10^{-12}$ e fm for proton [6, 7], and $|d_e| < 8.7 \cdot 10^{-16}$ e fm for electron [8]. In this context, there are proposals of direct measurements of EDMs of charged particles in dedicated storage rings [9–13]. However, a single measurement would not be sufficient to identify the source of TRV. For this reason, the measurement of EDMs of various light nuclei such as ^{2}H, ^{3}H and ^{3}He can help to impose constrains on the TRV sources.

The use of light nuclei as probes for TRV results to be advantageous because the nuclear physics of the systems is theoretically under control. In particular, the chiral effective field theory (χEFT) provides a systematic and perturbative scheme to study TRV nuclear effects treating all the possible sources [14–16]. Each Lagrangian term is associated to a low-energy constants (LECs) which must be determined fitting the experimental data. The χEFT approach permits not only to determine the TRV interactions but it provides also a systematic way to control the errors due to the truncation of the chiral expansion [21].

In this work, starting from the Lagrangian of Refs. [14–16] adding only the isotensor interactions we derived the chiral potential up to next-to-next-leading order (N2LO). The potential is then used to study the EDM of the three nucleon system, ^{3}H and ^{3}He, focusing in particular on the role of TRV three-body forces and in the estimation of the theoretical uncertainties. Such an approach provides a suitable framework for the future determination of the LECs.

2. The nuclear TRV potential

The relevant terms of the Lagrangian which can give contribution to the nuclear potential up to N2LO are [14–16],

$$\begin{aligned}\mathscr{L}_{\rm TRV} &= g_0\overline{\psi}\vec{\pi}\cdot\vec{\tau}\psi + g_1\overline{\psi}\pi_3\psi + g_2\overline{\psi}\pi_3\tau_3\psi + M\Delta\pi_3\pi^2 \\ &\quad -2i\overline{\psi}(d_0+d_1\tau_z)\gamma_5\sigma^{\mu\nu}\psi F_{\mu\nu} + \mathscr{L}^{NN}_{\rm TRV}\,, \end{aligned} \tag{2.1}$$

where $\mathscr{L}^{NN}_{\rm TRV}$ includes five contact interactions which permits us to take care of the exchange of heavier mesons and reabsorb the divergences in the potential. Further terms of the Lagrangian involving derivatives would give rise to potential terms which can be reabsorbed in those generated by the Lagrangian given in Eq. (2.1) [17]. Moreover, the calculation of the EDM requires the inclusion of the electromagnetic currents,

$$\mathscr{L}^{\gamma}_{\rm TRV} = -2\overline{\psi}\,(d_0+d_1\tau_3)\,\gamma_5\sigma^{\mu\nu}\psi F_{\mu\nu}\,, \tag{2.2}$$

from which we can define $d_p = (d_0 + d_1)/2$ and $d_n = (d_0 - d_1)/2$ which are the proton and neutron proper EDM.

We evaluate the T matrix in terms of time-ordered perturbation theory amplitudes whose associated diagrams are shown in Figure 1. The nuclear potential was then derived from the T matrix by inverting order by order in the power counting the Lippman-Schwinger equation. The leading order

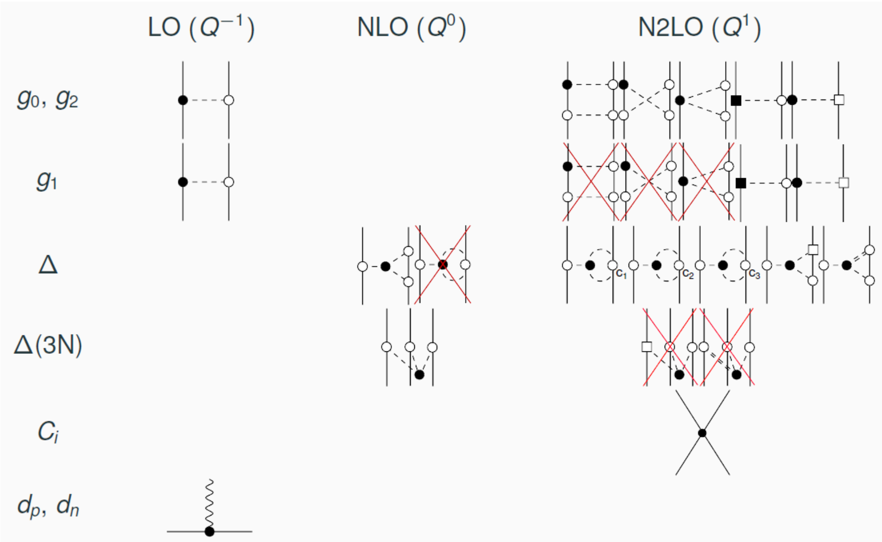

Figure 1: Time-ordered diagrams contributing to the TRV potential. Nucleons and pions are denoted by solid and dashed lines, respectively. The open (solid) circle represents a PC (TRV) vertex. The squares represent NLO vertices, while the double dashed lines recoil corrections coming from the energy denominators.

(LO) of the potential is given by the one pion exchange (OPE) associated to the LECs g_0, g_1 and g_2. The two pion exchange (TPE) contribution coming from these LECs appears only for g_0 and g_2 as already observed in Ref. [18]. The three pion vertex (TPV) gives rise to contribution at order Q^0 but also of order Q^1 when the LECs c_1, c_2 and c_3 of the parity conserving (PC) Lagrangian, are taken into account. The TPV vertex generates also three body forces at order Q^0 while at order Q^1 all the time ordered diagrams cancel. The contribution of the contact terms appear at N2LO while the single nucleon contribution at LO. The final expression of the potential contains 11 LECs which must be determine from the experiment. The potential is then regularized introducing a regularization function $C_\Lambda(k) = \mathrm{e}^{-(k/\Lambda)^4}$. Three cutoff values are considered $\Lambda = 450$, 500, 550 MeV.

3. The EDM of ^{3}H and ^{3}He

In this section we present the results for the EDM of the trinucleon system. The EDM of each nucleus can be expressed as the product of the LECs with numerical coefficients which contains all the dynamics given by the potential, namely,

$$d^A = g_0 a_0 + g_1 a_1 + g_2 a_2 + \Delta a_\Delta + d_p a_p + d_n a_n + \sum_{i=1,5} C_i A_i \,. \tag{3.1}$$

where the C_i are the LECs which comes from the contact terms. In the calculation of the coefficients we use the various chiral order of the *NN* PC potential of Ref. [19] and for the three-nucleon PC potential the N2LO with the c_E and c_D LECs fitted in Ref. [20]. We evaluate also the theoretical errors associated with the chiral expansion truncation of the nuclear potential. We express the error on the numerical coefficients for the trinucleon systems as,

$$(\delta a_i)^2 = (\delta a_i^{\mathrm{PC}})^2 + (\delta a_1^{\mathrm{TRV}})^2 + (\delta a_i^{\psi})^2 \tag{3.2}$$

where δa_i^{PC} is the error associated to the chiral expansion of the PC potential and $\delta a_i^{\mathrm{TRV}}$ the error associated with the chiral expansion of the TRV potential. Both the contributions were evaluated following the prescriptions of Ref. [21] where as reference momentum in the calculation of the errors we used the mass of the pion. Moreover we we introduce an error related to the uncertainties on the wave function δa_i^{ψ} which we estimated to be of the order of $\sim 1\%$. It is straightforward to understand that the errors are dominated by the TRV part because we are using the N2LO potential for it and the N4LO potential for the PC part.

The results for some of the coefficients of ^{3}H are shown in Figure 2 while for the ^{3}He in Figure 3.

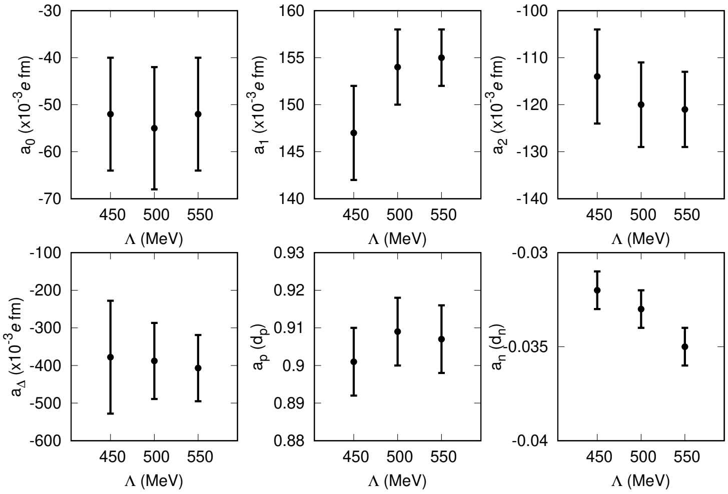

Figure 2: Values of selected coefficients a_i for ^{3}H. The error bars are evaluated following Ref. [21].

From the Figures it is possible to observe that the dependence on the cut-off is small, since all the results for a given a_i are compatible within the theorethical uncertainties. Note the huge errors reported for the coefficients a_Δ which are due to the fact that the N2LO diagrams give a correction of $\sim 70\%$, quite far away from what predicted by chiral perturbation theory. This effect is mainly due to the large contribution of the diagrams in which the c_1, c_2, and c_3 LECs [17] of the PC potential appear. We found that the TRV 3-body forces enhanches of the order of $\sim 25\%$ the pure two-body contribution at NLO. This is an order of magnitude larger than the result reported in Ref. [22] however the discrepancy is not yet understood. The contribution of the TPE diagrams to a_0 and a_2 are of the order of $\sim 45\%$ and $\sim 40\%$ respectively which is larger than expected from

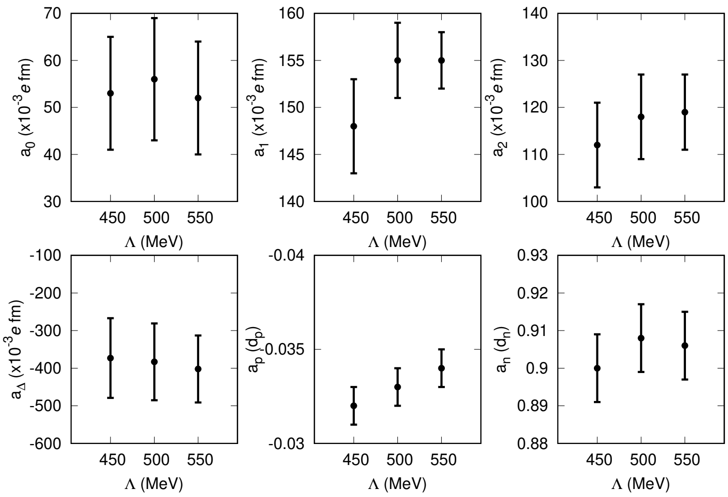

Figure 3: Values of selected coefficients a_i for ^{3}He. The error bars are evaluated following Ref. [21].

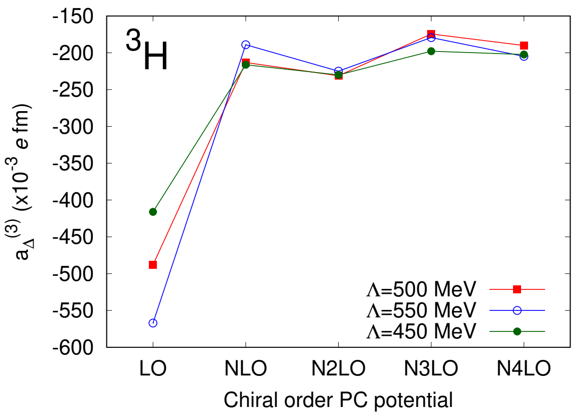

Figure 4: Values of the TRV 3-body contribution to a_Δ for the ^{3}H nucleus and for the three choice of the cutoff when varying the chiral order of the PC potential.

the chiral convergence and they are due mainly to the box diagrams of Figure 1. The errors of the a_1 coefficients results to be smaller compare to a_0 and a_2 because only relativistic corrections give contribution at N2LO. As reguarding a_p and a_n the error are mainly due to the uncertainties on the wave functions.

Moreover, we studied the effect of the PC potential on the EDM and we observe that the values evaluated with the N2LO, N3LO and N4LO PC potential differ by less than 5% which confirm the robustness of the calculation. As example, in Figure 4 we report the value of the contribution of the TRV three body forces to a_Δ coefficient calculated with different chiral order of the PC potential and for the three different choices of the cutoff.

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