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# Study of fundamental symmetries in the few-nucleon systems

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**Abstract.** In this contribution we present two studies of fundamental symmetries in light nuclei: the investigation of CP violation via the calculation of the electric dipole moments (EDMs) of the deuteron, $^3$H and $^3$He, and the possible existence of a new bosonic particle, the so-called X17, in the $^3\mathrm{H}(p,e^+e^-)^4\mathrm{He}$ and $^3\mathrm{He}(n,e^+e^-)^4\mathrm{He}$ reactions. The advantage to perform these investigations in few-nucleon systems is related to the possibility to compute accurate *ab initio* bound- and continuum-states wave functions using well established nuclear interactions. Therefore, if these effects are observed, they can be unambiguously related to underlying beyond Standard Model theories.

## 1. Introduction

Few-nucleon systems play an important role in Nuclear Physics, as for those systems it is possible to compute accurate *ab initio* bound- and continuum-state wave functions. This has allowed, first of all, the development of more and more accurate nucleon-nucleon (NN) and three-nucleon (3N) interactions, by exploiting detailed comparison with huge databases of scattering observables in $A = 2, 3, 4$ systems.

Clearly, the knowledge of the nuclear interaction is at the heart of nuclear physics and has been a subject of great scientific interest since many decades. In recent years, the development of chiral effective field theory ($\chi$EFT) [1] has given a new impetus to the derivation of nuclear interactions [2, 3]. The $\chi$EFT approach utilizes the spontaneously broken approximate $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R$ chiral symmetry of Quantum Chromodynamics (QCD) in order to describe low-energy dynamics of pions, the (pseudo-) Goldstone bosons of the spontaneously broken axial generators, in a systematic and model-independent fashion within the framework of the effective chiral Lagrangian [4, 5, 6, 7, 8], see Refs. [9, 10] for review articles. Very accurate NN and 3N chiral interactions are nowadays available [3, 11, 12, 13], although studies to improve the 3N force are still ongoing [14, 15, 16, 17].

In addition to the bulk interactions mentioned above, nuclear forces also feature much tinier components, which originate from the weak forces between quarks and/or physics beyond the standard model (BSM) and whose strength is smaller than that of the strong and electro-magnetic (EM) interactions by many orders of magnitude. These tiny components are, nevertheless, extremely interesting since investigation of their effects may shed new light on fundamental symmetries and BSM physics. The effects of such exotic components can be revealed by measuring specific observables which would vanish if these symmetries were conserved. In this contribution, we consider the effect of parity and time-reversal violating

(PTV) nuclear forces and discuss how they can be evidenced by studying the electric dipole moments (EDMs) of light nuclei. In particular, time-reversal violation is related to CP violation. Therefore, the interest of this study is related to important questions, as for example, the matter-antimatter asymmetry in the universe [18]. As we will show later, CP violation can originate from many sources. It is therefore important to study as many PTV observables as possible, in addition to the EDMs of electrons and neutrons.

But few-nucleon systems can be used also to reveal the possible existence of new particles. Nowadays, there is an intense theoretical and experimental effort at identifying the so-called dark matter (DM), see, for example, Ref. [19] and references therein. Recently there were claims [20, 21, 22, 23] that an unknown boson particle (denoted as "X17") had been observed in the processes $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ and $^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$ at the ATOMKI experimental facility situated in Debrecen (Hungary). These claims were based on a $\approx 7\sigma$ excess of events in the angular distribution of leptonic pairs produced in these reactions, which have a $Q$-value of about 20 MeV. In fact, this excess could be explained by positing the emission of an unknown boson with a mass of about 17 MeV decaying into $e^+e^-$ pairs.

In the present contribution, we present a study of the $^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$ and $^3\mathrm{He}(n, e^+e^-)^4\mathrm{He}$ reactions, by accurately taking into account the four-body dynamics [24, 25, 26], and employing modern nuclear interactions derived within the framework of $\chi$EFT discussed earlier [3, 11, 12, 13]. To perform this study, we need of accurate $\chi$EFT electromagnetic currents, as well. We have taken them from Refs. [27, 28, 29, 30, 31].

This paper is organized as follows. In Sec. 2 we discuss the various sources of CP violation and present the calculation of the EDMs of ligh nuclei. In Sec. 3, we present the study of the $^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$ and $^3\mathrm{He}(n, e^+e^-)^4\mathrm{He}$ reactions and discuss how the cross sections are affected by the spin and parity of the X17. Finally, conclusions and perspectives of the present studies are reported in the last section.

## 2. EDM of light nuclei

In this section, we first introduce the various sources of CP violation at microscopic level, then briefly discuss how these sources give origin to a PTV component of the nuclear force, and finally present results of the calculations of EDMs for some light nuclei.

### *2.1. CP violation at microscopic level*

In the Standard Model (SM) with three generations of quarks, CP is broken by the phase of the CKM matrix, which explains all the observed CP violation in the kaon [32, 33, 34], and $B$ meson systems [35, 36]. The phase of CKM gives, on the other hand, unobservable contributions to flavor-diagonal CP violation, in particular to the neutron [37, 38, 39] and electron EDMs [40, 41, 42].

The second source of CP violation in the SM is the QCD $\theta$ term [43, 44, 45],

$$\mathcal{L}^{\theta}_{PTV} = -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} , \tag{1}$$

where $g_s$ is the strong coupling constants and $G^a_{\mu\nu}$ the gluon field tensors ($a$ is a color index). The $\theta$ term is a total derivative, but it contributes to physical processes through extended, spacetime-dependent field configurations known as instantons. The current limit on the neutron EDM, on the other hand, sets a stringent limit on $\theta$, namely $|\theta| < 10^{-10}$ [46].

The phase of the CKM and the QCD $\theta$ term are the only CP-violating parameters in the SM Lagrangian. They are however not sufficient to explain the observed matter-antimatter asymmetry of the Universe [47, 48, 49, 50], and it is therefore natural to think about CP-violating sources induced by BSM physics. The low-energy CP-violating operators ($SU(3)_c \times U(1)_{\mathrm{em}}$-invariant) relevant for EDMs have been cataloged in several works, e.g. Refs. [51, 52, 53, 54, 55].

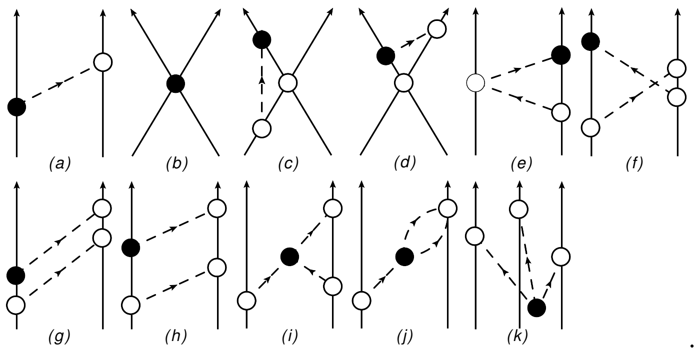


**Figure 1.** Time-ordered diagrams contributing to the PTV potential (only a single time ordering is shown). Nucleons and pions are denoted by solid and dashed lines, respectively. The open (solid) circle represents a strong (PTV) vertex.

The most important (dimension-six operators) are a three-gluon term, the nucleon EDMs, and various four-quarks operators. All these terms are multiplied by (unknown) PTV coupling constants (for a review, see Ref. [56]).

### *2.2. The PTV nuclear potential*

The $\theta$-term and the six-dimensional operators which violate parity and CP symmetry transform differently under isospin and chiral rotations [57]. One can exploit this fact to construct hierarchies of $\chi$EFT Lagrangians involving nucleons and pions [58, 59, 57]. Starting from them, it is possible to construct PTV NN and 3N potentials. These potentials are given in terms of a sum of diagrams, which can be obtained either using the method of unitary transformation [2], standard dimensional regularization [60] or the time-ordered perturbation theory (TOPT) method [61].

At each diagram can be assigned a "chiral order" $\sim Q^\nu$, where $Q$ is a low-energy scale and $\nu$ an integer number. The TOPT diagrams that give contribution to the NN PTV potential up to $\text{N}^2$LO (order $Q^1$) are shown in Fig. 1. For example, the one-pion-exchange (OPE) diagram (a) corresponds to a contribution of lowest order (LO), namely $Q^{-1}$; diagram (i) with a three-pion vertex is of order $Q^0$, namely at next-to-leading order (NLO). The other diagrams are of order $Q$, namely they bring contributions at next-to-next-to-leading order ($\text{N}^2$LO).

Each PTV vertex corresponds to an hadronic PTV coupling constant, also called low-energy constant (LEC). These are: $d_p$ and $d_n$, the proton and neutron EDMs, $\bar{g}_{0,1,2}$ the pion-nucleon coupling constants, $\bar{C}_{1-5}$ the nucleon-nucleon contacts terms, and $\bar{\Delta}$ is the three-pion coupling constant. All these LECs can be related to the parameters entering the quark PTV Lagrangian terms described in the previous subsection [58, 60, 62, 57, 56]. Since the PTV coupling constants are supposed to be very tiny, it is customary to retain only the diagrams which are linear on them.

### *2.3. EDMs of light nuclei*

The EDM of an $A$ nucleus, due to the smallness of the PTV LECs, can be expressed as

$$\begin{aligned} d^A &= d_p a_p + d_n a_n + \bar{g}_0 a_0 + \bar{g}_1 a_1 + \bar{g}_2 a_2 \\ &+ \bar{C}_1 A_1 + \bar{C}_2 A_2 + \bar{C}_3 A_3 + \bar{C}_4 A_4 + \bar{C}_5 A_5 + \bar{\Delta} a_\Delta \,, \end{aligned} \tag{2}$$

where the $a_i$ for $i = 0, 1, 2$, $A_i$ for $i = 1, \ldots, 5$, $a_\Delta$, and $a_p$, $a_n$ are coefficients independent on the LEC values (all coefficients except $a_p$ and $a_n$ have the unit of a length).

| | $a_n$ | $a_p$ | $a_0$ [fm] | $a_1$ [fm] | $a_2$ [fm] | $A_1$ [fm] | $A_2$ [fm] | $A_3$ [fm] | $A_4$ [fm] | $A_5$ [fm] | $a_\Delta$ [fm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $^2$H | 0.939 | 0.939 | | 0.200 | | | | 0.013 | −0.013 | | −0.304 |
| $^3$H | −0.033 | 0.909 | −0.053 | 0.158 | −0.119 | 0.006 | −0.010 | −0.008 | 0.013 | −0.022 | −0.343 |
| $^3$He | 0.908 | −0.033 | 0.054 | 0.158 | 0.119 | −0.006 | 0.010 | −0.008 | 0.013 | 0.022 | −0.339 |

**Table 1.** Values of the coefficients entering the expression of the deuteron, $^3$H and $^3$He EDMs calculated for the $\chi$EFT N$^2$LO PTV potential described in this work and the strong potential derived in Ref. [63]. The cutoff for both the strong and PTV potentials has been chosen to be $\Lambda_C = 500$ MeV.

The numerical coefficients entering the expression of the deuteron, $^3$H and $^3$He EDMs are summarized in Table 1. Once the EDMs of these nuclei will be measured, these expressions can be used to extract the values of the LECs $\bar{g}_{0,1,2}$, $\bar{C}_{1-5}$, and $\bar{\Delta}$, and from them, to obtain information on the different sources of CP violation described in subsection 2.1.

## 3. The X17 anomaly

As discussed in the Introduction, there have been claims for the existence of a bosonic particle in some nuclear reactions. Here, we present a study of the $^3\mathrm{H}(p,e^+e^-)^4\mathrm{He}$ and $^3\mathrm{He}(n,e^+e^-)^4\mathrm{He}$ reactions and discuss how the cross sections are affected by the spin and parity of the X17.

### *3.1. X17 interaction at microscopic level and with the hadrons*

In general, the SM-X17 interaction Lagrangian density is written as

$$\mathcal{L}^c_{f,X}(x) = e \sum_{f=e,u,d,\ldots} \varepsilon_f\, \overline{f}(x)\, \Gamma^c\, f(x)\, X_c(x)\ , \tag{3}$$

where $c = S, P, V$, or $A$ for a scalar, pseudoscalar, vector, or axial boson, respectively. Correspondingly,

$$\Gamma^{c=S,P,V,A} = 1, i\,\gamma^5, \gamma^\mu, \gamma^\mu\,\gamma^5\ . \tag{4}$$

In Eq. (3) $f(x)$ is the field of the SM particle (electron, quarks, etc.), while $X_c(x) = X(x)$ for $c = S, P$ and $X_c(x) = X_\mu(x)$ for $c = V, A$ represents the X17 field. The single coupling constant $\varepsilon_e$ is written in units of the electric charge $e > 0$ ($e^2 = 4\pi\alpha$).

The X17 boson must decay promptly in $e^+$-$e^-$ pairs for these to be detected inside the experimental setup. This observation actually introduces a *lower limit* to the possible values of $\varepsilon_e$. These limits are also established by various electron beam-dump experiments (see, for example, Ref. [64] and references therein). For $M_X \approx 17$ MeV, the most stringent lower bound, $|\varepsilon_e| > 2 \times 10^{-4}$, comes from the SLAC E141 experiment [65], while the upper bound $|\varepsilon_e| < 2 \times 10^{-3}$ has been set by the KLOE-2 experiment [66]. In the following, we will assume $\varepsilon_e = 10^{-3}$, fix $\varepsilon_u$ and $\varepsilon_d$ to fit the 2019 ATOMKI data [21], and study how the angular distribution of the two leptons is affected by the values of the spin and parity of the X17 boson varying the energy of the beam.

From the interaction Lagrangians given in Eq. (3), it is possible to derive hadron-X17 interaction Lagrangian densities in the framework of $\chi$EFT. By retaining only leading-order contributions (and selected subleading ones in the vector and pseudoscalar cases), one obtains the following hadron-X17 interaction Lagrangians (for a detailed derivation, see Ref. [67])

$$\mathcal{L}^S_X(x) = e\,\overline{N}(x)[\eta^S_0 + \eta^S_z\,\tau_3]N(x)\,X(x)\ , \tag{5}$$

$$\mathcal{L}^P_X(x) = e\,\eta^P_z\,\pi_3(x)\,X(x) + e\,\eta^P_0\overline{N}(x) i\,\gamma^5 N(x)\,X(x)\ , \tag{6}$$

$$\begin{aligned}\mathcal{L}_X^V(x) &= e\,\overline{N}(x)[\eta_0^V + \eta_z^V\,\tau_3]\gamma^\mu\,N(x)\,X_\mu(x) \\ &\quad + \frac{e}{4\,m_N}\,\overline{N}(x)[\kappa_0\eta_0^V + \kappa_z\eta_z^V\tau_3]\sigma^{\mu\nu}\,N(x)F_{\mu\nu}^X(x)\ , \end{aligned} \tag{7}$$

$$\mathcal{L}_X^A(x) = e\,\overline{N}(x)[\eta_0^A + \eta_z^A\,\tau_3]\gamma^\mu\gamma^5\,N(x)\,X_\mu(x)\ , \tag{8}$$

where $m_N$ is the nucleon mass, $N(x)$ is the iso-doublet of nucleon fields, $\pi_3(x)$ is the third component of the triplet of pion fields, and $F_{\mu\nu}^X(x) = \partial_\mu\,X_\nu(x) - \partial_\nu\,X_\mu(x)$ is the X17 field tensor. The hadron-X17 coupling constants $\eta_0^c$ and $\eta_z^c$ are linear combinations of the quark-X17 coupling constants $\varepsilon_u$ and $\varepsilon_d$, see Ref. [67] for their explicit expressions. In the vector case, we have included also the subleading term proportional to $F_{\mu\nu}^X$ and where

$$\kappa_0 = \kappa_p + \kappa_n\ , \qquad \kappa_z = \kappa_p - \kappa_n\ , \tag{9}$$

$\kappa_p$ and $\kappa_n$ being the anomalous magnetic moments of the proton and neutron, respectively. From this Lagrangians, it is easy to introduce the effect of the emission/decay of the X17 boson in a nuclear transition.

### 3.2. *The* $^3$H$(p, e^-e^+)^4$He *and* $^3$He$(n, e^-e^+)^4$He *cross sections*

The amplitude for such processes can be written as

$$T_{fi} = T_{fi}^{EM} + T_{fi}^X\ , \tag{10}$$

where $T_{fi}^{EM}$ is the amplitude coming from the emission of a virtual gamma, while $T_{fi}^X$ the amplitude due to the emission of an X17 with its successive decay in the $e^+e^-$ pair. Using the Fermi Golden Rule, it is not difficult now to calculate the five-fold cross section (the final state is composed by three particles). The four-fold differential cross section, obtained by integrating over the electron energy, remains function of the polar angles of the two leptons [67]. In the following, we consider the two leptons emitted in the plane orthogonal to the incident beam, as for the ATOMKI experiments, and plot the four-fold cross section as function of the angle $\theta_{ee}$ between the two leptons. For $\theta_{ee} < 90°$, the kinematical conditions do not allow the emission of the X17, therefore the cross section is completely determined by the EM amplitude, which has no free parameters. Since the ATOMKI cross section measurements are unnormalized, we rescale them to match the calculated values for $\theta_{ee} < 90°$.

Then, for each of the assumed spin and parity of the X17, we constrain one of the coupling constant $\eta_{0,z}^c$ (or a combination of them) by fitting the 2019 ATOMKI data [21] obtained at an incident proton energy of 0.9 MeV and in the range $\theta_{ee} > 110°$, where the (purported) X17 signal has been observed (we take as before $M_X = 17$ MeV). Constraining $\eta_{0,z}^c$ is equivalent to constrain a combination of $\varepsilon_{u,d}$ due to the aforementioned linear relation between them.

The calculated cross sections for both $^3$H$(p, e^+e^-)^4$He and $^3$He$(n, e^+e^-)^4$He reactions at a number of incident proton and neutron energies are reported in Fig. 2. In computing the cross sections, we have taken the width $\Gamma_X$ from the X17 decay into $e^+$-$e^-$ pairs; however, we have folded the resulting calculated values with a Gaussian, in order to account for the finite angular resolution (for more details, see Ref. [67]).

As it can be seen by inspecting the figure, the height of the X17 peak behave differently changing the energy of the beam for the different cases. For the S case, the peak is higher at low energy, while for the P and A cases is more evident for the $^3$He$(n, e^-e^+)^4$He process at 0.17 MeV neutron incident energy. This behavior depends on which resonance of $^4$He is populated [67]. An experiment is in construction at the n_ToF facility at CERN [69] in order to exploit this different energy dependence of the height of the peak in order to extract information on the nature of X17, if the observed signal at ATOMKI will be eventually confirmed.

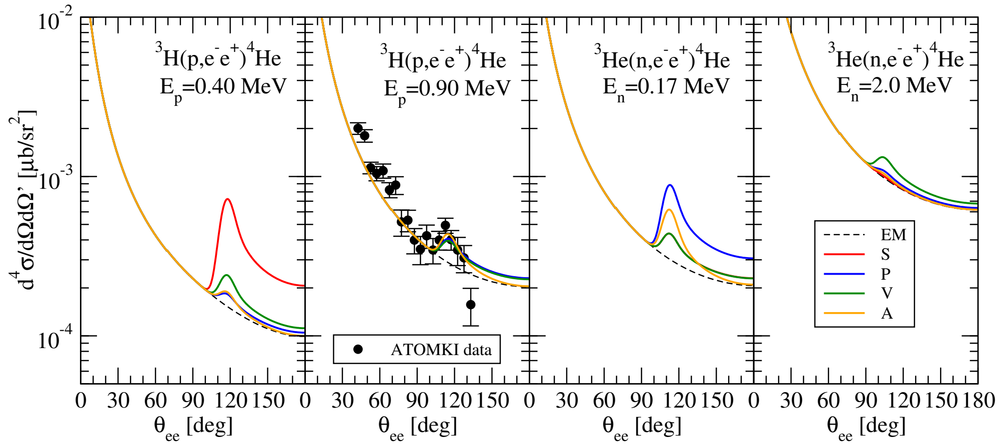


**Figure 2.** The four-fold differential cross section for the $^3\mathrm{H}(p,e^-e^+)^4\mathrm{He}$ and $^3\mathrm{He}(n,e^-e^+)^4\mathrm{He}$ processes at four different incident nucleon energies for the configuration in which the $e^+$ and $e^-$ momenta are in the plane orthogonal to the incident nucleon momentum and as function of the angle $\theta_{ee}$ between them. The two left panels report the results obtained for the $^3\mathrm{H}(p,e^-e^+)^4\mathrm{He}$ reaction at incident proton energy of 0.40 and 0.90 MeV, respectively, while the two right panels the results obtained for the $^3\mathrm{He}(n,e^-e^+)^4\mathrm{He}$ reaction at neutron incident energy 0.17 and 2.0 MeV, respectively. Moreover, the curves labeled S, P, V, and A show the results obtained by including the exchange of a scalar, pseudoscalar, vector, and axial X17, respectively. In all cases, we have taken $M_X = 17$ MeV and $\Gamma_X$ as given from the X17 decay in $e^-e^+$, and have adjusted the coupling constants so as to reproduce the ATOMKI $^3\mathrm{H}(p,e^-e^+)^4\mathrm{He}$ cross section data of Ref. [21] at the incident proton energy of 0.90 MeV. The dashed (black) curves show the results obtained by including the electromagnetic amplitude only. The calculations are based on the N3LO nucleon-nucleon interaction of Refs. [68, 3], augmented by the N2LO three-nucleon interaction defined in Ref. [11], and accompanying electromagnetic currents. [27, 28, 29].

## 4. Concluding remarks

In this contribution we have presented *i)* the calculations of EDMs of light nuclei, with the aim of studying eventual effects related to CP violation, and *ii)* the $^3\mathrm{H}(p,e^+e^-)^4\mathrm{He}$ and $^3\mathrm{He}(n,e^+e^-)^4\mathrm{He}$ reactions, in order to investigate the existence of a new bosonic particle, the X17. Using $\chi$EFT to relate the interactions at the nuclear level with those of the underlying theories, and using accurate bound and continuum wave function available in these few-nucleon systems, we hope to obtain information on CP violation and a possible DM candidate.

We note that currently there are proposals for the direct measurement of EDMs of electrons, single nucleons and light nuclei in dedicated storage rings [70, 71, 72, 73, 74]. This new approach plans to reach an accuracy of $\sim 10^{-16}$ $e$ fm, improving the sensitivity in particular in the hadronic sector. Regarding the X17, there are several experiments (n_ToF [69], MEGII [75], DarkLight [76], SHiP [77], the "Montreal X-17 Project" [78], TREK/E36 [79] and others [19]) planning specifically to search for such a light boson. In addition, large collaborations, such as BelleII [80], NA64 [81], and others, are dedicating part of their efforts in an attempt to clarify this issue. In case of either a successful measurement of an EDM of a light nucleus, or of the eventual confirmation of the X17 signal, the present theoretical calculations will allow an accurate analysis of the experimental results in terms of SM or BSM coupling constants.

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