Electric Dipole Moments as Probes of *CPT* Invariance

Pavel A. Bolokhov[*,†] and Maxim Pospelov[*]

[*]*Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 1A1, Canada*
[†]*Theoretical Physics Department, St.Petersburg State University, Ulyanovskaya 1, Peterhof, St.Petersburg, 198504, Russia*

Abstract. Electric dipole moments (EDMs) of elementary particles and atoms probe violations of T and P symmetries and consequently of CP if CPT is an exact symmetry. We point out that EDMs can also serve as sensitive probes of CPT-odd but CP-even interactions. In a class of theories where the breaking of CPT is introduced via the breaking of Lorentz invariance, we identify the leading dimension five operators that induce non-zero EDMs. We find that the EDMs of neutrons, and heavy diamagnetic atoms provide best sensitivity to the T, P, CPT-odd interactions, allowing to probe energy scales as high as 10^{12} GeV. We also point out that additional tests of Lorentz invariance are required in order to distinguish between CP-odd and CPT-odd effects, should non-zero EDMs be found.

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INTRODUCTION

Tests of fundamental symmetries play an important role in discerning the properties of nature at ultra-short distance scales. Searches for Electric Dipole Moments (EDMs) provide a profound test of P and T symmetries. Conventionally, an EDM for a neutral particle of spin S is represented as

$$H = -\mu\mathbf{B}\cdot\frac{\mathbf{S}}{S} - d\mathbf{E}\cdot\frac{\mathbf{S}}{S}\,.$$

Therefore, a non-zero d generically involves violation of time and space reversal parities.

We argue, that if CPT invariance is broken at an ultra-high energy scale (by means of Lorentz invariance breaking), it leads to an EDM-inducing interaction, which is odd under C, P and T. A generic EDM Lagrangian for a particle with a spin 1/2 can be written as

$$\mathscr{L}_{\rm EDM} = -\frac{i}{2}d_{\rm CP}\overline{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi \;+\; d_{\rm CPT}\overline{\psi}\gamma_\mu\gamma_5\psi F_{\mu\nu}n^\nu\,, \qquad (1)$$

where n^μ is a background vector. This implies that, in general, EDM searches provide a constraint on the sum $d_{\rm CP} + d_{\rm CPT}$. We discuss the structure of the effective CPT-odd and CP-even Lagrangian in the presence of external vector and tensor sources, and extract their consequences for the most sensitive EDM searches. In particular, we argue that, should a non-zero result be detected in the next generation EDM experiments, one will be able to distinguish between the CP-odd and CPT-odd contributions.

CPT-ODD, CP-EVEN INTERACTIONS

In the framework where CPT violation is mediated by Lorentz violation, CPT-odd interaction terms appear at dimension three and dimension five level. However, only the dimension five operators induce EDM-like interactions. The corresponding operators that couple to vector backgrounds are

$$\mathscr{L}_{\rm CPT}^{\rm vector} = \sum_{i=u,d,s} d_i^\mu \cdot \bar{q}_i \gamma^\lambda \gamma^5 F_{\lambda\mu} q_i \,, \tag{2}$$

where d_i^μ are the background vectors, generically different for all flavors. Here only the interactions involving quarks enter. The analogous operators in the lepton sector vanish on the equations of motion, owing to the fact that the electromagnetic field strength can be written as a commutator of two gauge derivatives acting on the lepton.

If one also admits tensor Lorentz-violating backgrounds, the CPT-odd sector with EDM-signatures broadens:

$$\mathscr{L}_{\rm CPT}^{\rm tensor} \;=\; \sum_{i=u,d,s,e,\mu} D_q^{\mu\nu\rho} \cdot \overline{\psi}_i \gamma_\mu F_{\nu\rho} \gamma^5 \psi_i \;+\; \sum_{i=u,d,s} \widetilde{D}^{\mu\nu\rho} \cdot \overline{\psi}_i \gamma_\mu G^a_{\nu\rho} t^a \gamma^5 \psi_i \,. \tag{3}$$

Here $D^{\mu\nu\rho}$ and $\widetilde{D}^{\mu\nu\rho}$ are irreducible tensors, symmetric in $(\mu\nu)$. It is noticeable that the interactions (2) and (3) preserve chirality. The conventional CP-odd EDM mixes left- and right-handed fermions and thus, to be embedded in the Standard Model, requires a Higgs vev insertion, so that $d_{\rm CP} \propto m_q \Lambda_{\rm CP}^{-2}$. In contrast, the CPT-odd physics decouples only linearly, $d_{\rm CPT} \propto \Lambda_{\rm CPT}^{-1}$. Combining the current limits on neutron EDM with the linear decoupling properties, one achieves the sensitivity to the scales of CPT violation as large as

$$\Lambda_{\rm CPT} \;\sim\; 10^{11} - 10^{12}\ \text{GeV}. \tag{4}$$

SIGNATURES OF CPT-ODD EDM'S

Vector backgrounds. The CPT-odd quark interactions (2) induce an EDM for the neutron. To estimate this contribution, one needs matrix elements of the axial-vector charges of light quarks inside a nucleon, for which a combined analysis of deep-inelastic scattering and the hyperon β-decay is available [1]. To a $\sim$20% accuracy we get

$$d_n = 0.8 d_d^0 - 0.4 d_u^0 - 0.1 d_s^0. \tag{5}$$

EDMs of diamagnetic atoms have a suppression (relative to the CP-odd case, where they are competitive with d_n) due to the preserved chirality — the Schiff moment is induced by the EDMs of nucleons and *not* by the π-exchange. For the case of Hg, we have

$$d_{\rm Hg} \;\simeq\; -5\times 10^{-4}(d_n + 0.1 d_p) \;=\; -5\times 10^{-4}(0.74 d_d^0 - 0.32 d_u^0 - 0.11 d_s^0). \tag{6}$$

From (5) and (6) and the current experimental limits $|d_n| < 6\times 10^{-26} e$cm and $|d_{\rm Hg}| < 2\times 10^{-28} e$cm, we conclude that CPT-odd EDMs of quarks are limited at $O(10^{-25} e\text{cm})$ level modulo significant cancellations between different terms in (5) and (6).

Concurrent measurements of deuteron and neutron EDMs open an important possibility of distinguishing the *CPT*-odd contributions from the *CP*-odd ones. The experiments measuring the EDM of the neutron, in the case of a non-zero signal, will yield a result which is the sum of both types of contributions. However, the deuteron EDM searches [2] will measure the resonant precession of the spin of deuterons in a storage ring, and it turns out that the *CPT*-odd contribution to the precession is additionally suppressed by the anomalous magnetic moment of the deuteron [3], $a = -0.143$. Thus, by comparing results from the two experiments, one will be able to separate the *CPT*-odd contribution to the EDM.

The most stringent experimental constraints exist for the dimension *three* LV operators $b^\mu \cdot \overline{\psi}\gamma_\mu\gamma_5\psi$ [4]. Generically, the latter could be induced by dimension five interactions (2). The corresponding limits on b^μ are translated into the sensitivity to $\Lambda_{\rm CPT}$ in the $10^{12} - 10^{13}$ GeV range [3]. Then, a detectable signal from the *CPT*-odd EDMs induced by a vector background would also imply a sidereal modulation of spin precession frequencies detectable in clock comparison experiments.

Tensor backgrounds. The *CPT*-odd tensor interactions (3) also induce an EDM-like signature. For the neutron, the corresponding effective Hamiltonian reads

$$H = -\mu\mathbf{B}\cdot\frac{\mathbf{S}}{S} - \mathscr{D}^{ij}E_i\cdot\frac{S_j}{S}, \tag{7}$$

where $\mathscr{D}^{ik}$ is a traceless symmetric tensor formed from the quark background tensors $D_q^{\mu\nu\rho}$. The interaction (7) creates a correction to the spin precession frequency proportional to $E_iB_k\mathscr{D}^{ik}$, which changes its sign under the reversal of the electric field, and thus exhibits an EDM signature. On general grounds, one expects 12 and 24 hour modulations of the *CPT*-odd tensor contribution to the neutron EDM.

In the case of paramagnetic atoms, the electron *CPT*-odd interaction analogous to (7) is capable of inducing a mixing of orbitals of opposite parity and contribute to an atomic EDM. The direct calculation of the mixing matrix element shows that the induced electric dipole moment of a paramagnetic atom scales as $d_{\rm CPT} \sim \alpha^2 Z^3 \cdot d_e$ with the charge of the atom. In the case of Cesium, using a simplified set of atomic wavefunctions [5], one obtains

$$\frac{d_{\rm CPT}(\rm Cs)}{d_{\rm CPT}(\rm e)} \simeq 7\ , \tag{8}$$

which provides a constraint of $\left|\mathscr{D}_e^{ik}\right| \lesssim 10^{-25}e$cm on the tensor background.

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