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CP-violation and electric dipole moments

Matthias Le Dall · Adam Ritz

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Abstract Searches for intrinsic electric dipole moments of nucleons, atoms and molecules are precision flavour-diagonal probes of new CP-odd physics. We review and summarise the effective field theory analysis of the observable EDMs in terms of a general set of CP-odd operators at 1 GeV, and the ensuing model-independent constraints on new physics. We also discuss the implications for supersymmetric models, in light of the mass limits emerging from the LHC.

Keywords Electric dipole moments · T-violation · BSM physics

1 Introduction

Tests of fundamental symmetries provide some of our most powerful probes of physics beyond the Standard Model (SM). Indirect precision tests at nuclear or atomic scales are often sensitive to new physics at distance scales much smaller than are accessible directly at high-energy colliders. Our focus here is on the discrete symmetries: C (charge conjugation), P (parity) and T (time reversal), which are violated in very specific ways within the SM. Indeed, the weak interactions are the only measured source of violations of P, C and CP through the chiral $V-A$ structure of the couplings, and through the nontrivial quark mixing in the CKM matrix respectively. In particular, CP violation observed thus far can be consistently described by the single (physical) phase in the unitary three-generation CKM mixing matrix V. Its strength is characterized by the Jarlskog invariant, $J = \mathrm{Im}[V_{us}V_{cd}V_{cs}^{*}V_{ub}^{*}] \sim 3\times10^{-5}$ [0]. The SM also assumes Lorentz invariance, which under very mild assumptions implies that CPT is identically conserved, and thus CP violation implies T violation.

The SM in its minimal form allows for one other CP-odd interaction, associated with the QCD parameter $\bar{\theta}$ that we will discuss further below. However, no physical effects from this source have been observed, leading to stringent constraints, $\bar{\theta} < 10^{-10}$. This is the so-called strong CP problem. The extension of the SM to account

M. Le Dall · A. Ritz (presenter)
Dept of Physics & Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
E-mail: aritz@uvic.ca

Table 1 Current constraints within three representatve classes of EDMs.

Class	EDM	Current Bound
Paramagnetic	YbF	$\|\text{“}d_{\rm YbF}\text{”}\| < 1.3 \times 10^{-22} e\,{\rm cm}$ [0]
Paramagnetic	^{205}Tl	$\|d_{\rm Tl}\| < 9 \times 10^{-25} e\,{\rm cm}$ [0]
Diamagnetic	^{199}Hg	$\|d_{\rm Hg}\| < 3 \times 10^{-29} e\,{\rm cm}$ [0]
Nucleon	n	$\|d_n\| < 3 \times 10^{-26} e\,{\rm cm}$ [0]

for neutrino mass also allows for CP-odd phases in lepton mixing, which are as yet unmeasured.

The fact that CP is not a symmetry of the SM, as the CKM phase $\delta \sim \mathcal{O}(1)$, does not lessen its utility as a probe of new physics. Firstly, there is a strong motivation to search for new sources of CP-violation which could provide a dynamical explanation for the baryon asymmetry in the Universe. The Sakharov criteria require C and CP violation for successful baryogenesis and, while the SM itself does violate these symmetries, it apparently fails by many orders of magnitude in explaining the magnitude of the observed baryon to photon ratio $\eta_b/s \sim 10^{-10}$. Secondly, the way in which the Kobayashi-Maskawa mechanism limits the appearance of (large) CP violating effects to specific flavour-violating processes, allows flavour-diagonal CP-odd channels to emerge as a highly sensitive probe of new physics with minimal SM (i.e. CKM) background.

The primary observables in this case are the electric dipole moments (EDMs) of nucleons, atoms and molecules. For a particle with spin $\mathbf{S}$ in a magnetic field $\mathbf{B}$ and electric field $\mathbf{E}$, the non-relativistic interaction is dictated by the fact that $\mathbf{S}$ is the unique rest-frame vector,

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}. \tag{1}$$

The second interaction, with an intrinsic electric dipole moment d, violates both P and T and has never been observed. The strongest current EDM constraints are shown for three characteristic classes of observables in Table 1.

Searches for intrinsic EDMs have a long history, stretching back to the prescient work of Purcell and Ramsey [0] who first used the neutron EDM as a test of parity in nuclear physics, several years before parity-violation was indeed discovered in the weak interactions. Even beyond the empirical motivation for new CP-odd sources for baryogenesis, such sources appear quite generically in new physics scenarios introduced for other reasons, e.g. supersymmetric models. Indeed, it is only the specific field content of the SM which limits the appearance of CP-violation to the CKM phase and $\bar{\theta}$. The lack of any observation of a nonzero EDM has, on the flip-side, provided an impressive source of constraints on new physics. These range from the bound on $\bar{\theta} < 10^{-10}$ – which implies an as yet unresolved tuning in the Standard Model known as the strong CP problem – to a now rather lengthy body of literature on the constraints imposed, for example, on supersymmetric scenarios such as the MSSM. For many years, in the absence of direct collider probes, EDMs have constrained the size of CP-odd phases in generic supersymmetric scenarios to $\mathcal{O}(10^{-3} - 10^{-2})$, a tuning that appears rather unwarranted given the $\mathcal{O}(1)$ value of the CKM phase. With the LHC now probing these scenarios directly, it has become clear that the tension inherent in these EDM limits (and indeed many other precision tests) was pointing to the absence of many new SUSY particles below the TeV scale. In this contribution, we will review the linkage between observable EDMs and the sources of underlying CP-violation in a model-independent form (see e.g. [0] for further details), and discuss the current status of the constraints on new CP-odd sources in the TeV range.

In Section 2, we summarize the EDM constraints, and express them as a set of induced bounds on a generic class of CP-odd operators normalized at 1 GeV [0]. These limits can then be applied to constrain models of new physics. In Section 3, we recall the SM contributions to these EDMs from the nonzero CKM phase, and then turn to constraints on models of new physics. We focus on the current status of the SUSY CP problem, in the light of current mass limits from the LHC. Note that we consistently use natural units: $\hbar = c = 1$, so that all mass (or inverse length) scales can be expressed in terms of electron volts (eV).

2 CP-odd operators and electric dipole moments

In this section we will briefly review the relevant formulae for the observable EDMs in terms of CP-odd operators normalized at 1 GeV. Including the most significant flavour-diagonal CP-odd operators (see e.g. [0]) up to dimension six, the corresponding effective Lagrangian takes the form,

$$\mathcal{L}_{\rm eff} = \frac{\bar{\theta} g_s^2}{32\pi^2} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a} - \frac{i}{2}\sum_{i=e,\mu,u,d,s} d_i\ \overline{\psi}_i (F\sigma)\gamma_5\psi_i - \frac{i}{2}\sum_{i=u,d,s}\widetilde{d}_i\ \overline{\psi}_i g_s (G\sigma)\gamma_5\psi_i$$
$$+\frac{1}{3} w\ f^{abc} G^a_{\mu\nu}\widetilde{G}^{\nu\beta,b} G_\beta^{\ \mu,c} + \sum_{i,j=e,\mu,q} C_{ij} (\bar{\psi}_i\psi_i)(\psi_j i\gamma_5\psi_j) + \cdots \quad (2)$$

In this Lagrangian, F and G are the electromagnetic and gluon field strength tensors respectively, while ψ_i denotes the Dirac field of the various quarks and leptons with masses below the QCD scale. For a Dirac fermion, the EDM operator $d\bar{\psi}(F\sigma)\gamma_5\psi$ reduces to $d\mathbf{E}\cdot\mathbf{S}$ on inserting non-relativistic solutions for the massive Dirac spinor ψ. The presence of the other terms in (2) reflects the fact that electric dipoles of nucleons and nuclei are also sensitive to the gluonic structure of QCD. These terms, through various loop effects, can all generate EDMs for composite states such as the neutron, or various CP-odd nuclear moments. The $G\tilde{G}$ term, as it has a dimensionless coefficient $\bar{\theta} = \theta_{\rm QCD} - {\rm ArgDet}M_q$, is particularly dangerous leading to the strong CP problem and in what follows we will invoke the axion mechanism [0] which relaxes this term to zero. However, even without a dominant contribution from the θ-term, the higher-dimension sources such as EDMs (d_i) and chromo-EDMs ($\tilde{d}_i$) of quarks and leptons lead to numerous constraints on models of new physics due to their contributions to the observable EDMs. The purely gluonic term in the second line, the Weinberg operator, is a higher order generalization of the θ-term which can also be important in various regimes, while the final term summarizes a number of 4-fermi interactions. Semileptonic interactions of this type may be significant in paramagnetic systems as they induce contact interactions between electrons and nucleons of the form $C_S\bar{e}i\gamma_5 eNN$, that can contribute to atomic EDMs. We will briefly review the physics of this link in the remainder of this section.

The physical observables can be conveniently separated into three main categories, depending on the physical mechanisms via which an EDM can be generated:

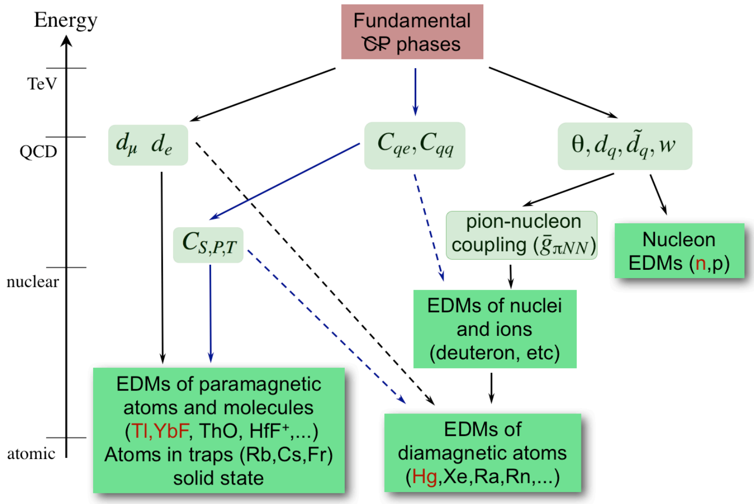

Fig. 1 A schematic plot of the hierarchy of scales between the leptonic and hadronic CP-odd sources and three generic classes of observable EDMs. The dashed lines indicate generically weaker dependencies in SUSY models.

EDMs of paramagnetic atoms and molecules; EDMs of diamagnetic atoms; and the neutron EDM. The inheritance pattern for these three classes is represented schematically in Fig. and, while the experimental constraints on the three classes of EDMs differ by several orders of magnitude, it is important that the actual sensitivity to the operators in (2) turns out to be quite comparable in all cases. This is due to various enhancement or suppression factors which are relevant in each case, primarily associated with various violations of "Schiff shielding" [0] – the non-relativistic statement that an electric field applied to a neutral atom must necessarily be screened and thus removes any sensitivity to the EDM.

EDMs of paramagnetic atoms and molecules :
For paramagnetic atoms, Schiff shielding is violated by relativistic effects which can in fact be very large. One has roughly [0],

$$d_{\rm para}(d_e) \sim 10\alpha^2 Z^3 d_e, \tag{3}$$

which for large atoms such as Thallium amounts to a huge enhancement of the field seen by the electron EDM (see e.g. [0,0]), which counteracts the apparently lower sensitivity of the Tl EDM bound,

$$d_{\rm Tl} = -585 d_e - e\ 43\ {\rm GeV} C_S^{\rm singlet}. \tag{4}$$

We have also included here the most relevant CP-odd electron-nucleon interaction, namely $C_S \bar{e} i\gamma_5 e \bar{N} N$, which in turn is related to the semileptonic 4-fermion operators in (2).

This relativistic enhancement of the internal field is boosted further in polar molecules, where a relatively small applied field can polarize the molecule leading to gigavolt internal fields. Since the response to the applied field is not linear, the induced effect is not strictly an EDM (we will denote it with quotation marks), but for comparison it scales parametrically as [0],

$$``d_{\rm mol}(d_e)" \sim 10\alpha^2 Z^3 \frac{M_{\rm mol}}{m_e} d_e \tag{5}$$

Recently, the Imperial College group has managed to limit the "EDM" of the polar molecule YbF [0], such it now sets the strongest constraint on the electron EDM,

$$``d_{\rm YbF}" = 1.3 \times 10^5 d_e + \mathcal{O}(C_{eq}) \tag{6}$$

Without cancelations this implies $|d_e| < 1.05 \times 10^{-27} e\,{\rm cm}$. Moreover, the very distinct contributions from semileptonic operators for Tl and YbF ensures that, even with cancelations, the slightly weaker limit $|d_e| < 1.6 \times 10^{-27} e\,{\rm cm}$ is robust.

EDMs of diamagnetic atoms :

For diamagnetic atoms, Schiff shielding is instead violated by the finite size of the nucleus and differences in the distribution of the charge and the EDM. However, this is a rather subtle effect,

$$d_{\rm dia} \sim 10 Z^2 (R_N/R_A)^2 d_{\rm nuc}, \tag{7}$$

and the suppression by the ratio of nuclear to atomic radii, R_N/R_A, generally leads to a suppression of the sensitivity to the nuclear EDM, parametrized to leading order by the Schiff moment S [0], by a factor of 10^3 (see e.g. [0,0]). Thus, although the apparent sensitivity to the Hg EDM is orders of magnitude stronger than for the Tl EDM, both experiments currently have comparable sensitivity to various CP-odd operators and thus play a very complementary role. Combining the atomic $d_{\rm Hg}(S)$, nuclear $S(\bar{g}_{\pi NN})$, and QCD $\bar{g}^{(1)}_{\pi NN}(\tilde{d}_q)$, components of the calculation [0,0], we have

$$d_{\rm Hg} = 7 \times 10^{-3}\, e\,(\tilde{d}_u - \tilde{d}_d) + 10^{-2}\, d_e + \mathcal{O}(C_S, C_{qq}). \tag{8}$$

Unfortunately, the overall uncertainty is rather large, a factor of 2-3 at least, due to uncertainties in the precision of the nuclear calculation of $S(\bar{g}_{\pi NN})$ [0], and significant cancelations between various contributions at the QCD level. Nonetheless, a valuable feature of $d_{\rm Hg}$ given the remarkable experimental precision is its sensitivity to the triplet combination of colour EDM operators $\tilde{d}_q$.

Neutron EDM :

The neutron EDM measurement is of course not sensitive to the above atomic enhancement/suppression factors. Using the results obtained using QCD sum rule techniques [0,0] (see also [0,0,0] for chiral approaches), wherein under Peccei-Quinn relaxation of the axion the contribution of sea-quarks is also suppressed at leading order[1]:

$$\begin{aligned} d_n &= (1.4 \pm 0.6)(d_d - 0.25 d_u) + (1.1 \pm 0.5) e (\tilde{d}_d + 0.5 \tilde{d}_u) \\ &\quad + 20\,{\rm MeV} \times e\; w + \mathcal{O}(C_{qq}). \end{aligned} \tag{9}$$

Note that the proportionality to $d_q \langle \bar{q}q \rangle \sim m_q \langle \bar{q}q \rangle \sim f_\pi^2 m_\pi^2$ removes any sensitivity to the poorly known absolute value of the light quark masses.

[1] Recently, in Ref. [0], a lattice QCD estimate for the nucleon coupling was inserted into the sum rule formula for d_n, which leads to a significant supression of the coefficient. However, we note there that this would also lead to a similar suppression of sum rules estimates for other measured nucleon data, e.g. the nucleon sigma term, and thus appears inconsistent.

Future developments :

As described in this symposium [0], the experimental situation is currently very active and a number of current EDM experiments are taking data, while several more are in development but close to the data-taking stage. These range from additional paramagnetic molecules such as ThO, to several new experiments searching for the neutron EDM, and also novel proposed searches for the EDMs of light charged nuclei and ions using storage rings [0]. This latter technique aims to avoid the effect of Schiff shielding and enhance sensitivity to the nuclear EDM and its hadronic constituents. A schematic summary of the sensitivity of a number of these new experiments to the set of CP-odd operators is exhibited in Fig. 1.

3 Constraints on new physics

Taking the existing bounds, and the formulae above, we obtain the following set of constraints on the CP-odd sources at 1 GeV (assuming an axion removes the dependence on $\bar{\theta}$ - see below) [0]:

$$\begin{aligned}
d_{\rm Tl} &\Rightarrow \left| d_e + e(26\,{\rm MeV})^2\left(3\frac{C_{ed}}{m_d}+11\frac{C_{es}}{m_s}+5\frac{C_{eb}}{m_b}\right)\right| < 1.6\times 10^{-27}\,e{\rm cm},\\
d_{\rm YbF} &\Rightarrow |d_e + \mathcal{O}(C_{eq})| < 1.05\times 10^{-27}\,e{\rm cm},\\
d_{\rm Hg} &\Rightarrow \left|(\tilde{d}_d-\tilde{d}_u)+\mathcal{O}(\tilde{d}_s,d_e,C_{qq},C_{qe})\right| < 3\times 10^{-27}\,{\rm cm},\\
d_n &\Rightarrow \left|e(\tilde{d}_d+0.56\tilde{d}_u)+1.3(d_d-0.25d_u)+\mathcal{O}(\tilde{d}_s,w,C_{qq})\right| < 2\times 10^{-26}\,e{\rm cm},
\end{aligned} \tag{10}$$

where the additional $\mathcal{O}(\cdots)$ dependencies are known less precisely, but may not always be subleading in particular models. The precision of these results varies from 10-15% for the Tl bound, to around 50-100% for the neutron bound, and to a factor of a few for Hg. It is remarkable to note that, accounting for the naive mass-dependence $d_f \propto m_f$, all these constraints are of a similar order of magnitude and thus highly complementary. Constraints obtained in the hadronic sector using other calculational techniques differ somewhat but generally give results consistent with these within the quoted precision. Indeed, setting aside issues of calculational precision, these bounds provide an essentially model-independent set of constraints on new CP-violating physics which may generate these operators at the 1 GeV scale. EDM measurements, even without a positive detection, therefore provide a suite of stringent constraints on new sources of CP-violation.

EDMs from the SM - CKM phase and $\bar{\theta}$:

It is worth reviewing the SM contributions to these EDMs. Starting with $\bar{\theta}$, currently the best sensitivity comes from the limit on the neutron EDM, and so we will just consider that observable. $d_n(\bar{\theta})$ was first computed using chiral techniques where it arises from an IR divergent pion loop [0] (see also [0]). It can also be determined using QCD sum rules [0], leading to a numerically similar result,

$$d_n(\bar{\theta}) = 2\times 10^{-16}\bar{\theta}\,e\,{\rm cm} \tag{11}$$

which leads to the current bound of $|\bar{\theta}| \lesssim 10^{-10}$.

In constrast to $\bar{\theta}$, the value of the CKM CP-violating Jarlskog invariant J is now quite well determined, and leads to distinct predictions for the EDMs. However, these generally arise at fairly high loop order, and are suppressed by quark mixing. We summarize the results of several computations with references below,

$$\begin{aligned} d_e(J) &\lesssim 10^{-38}(J/J_{\rm exp})\, e\,{\rm cm} \quad [0], \\ d_{\rm Hg}(J) &\sim (10^{-34} - 10^{-35})(J/J_{\rm exp})\, e\,{\rm cm} \quad [0], \\ d_n(J) &\sim (10^{-32} - 10^{-31})(J/J_{\rm exp})\, e\,{\rm cm} \quad [0], \end{aligned} \tag{12}$$

where $J_{\rm exp} \sim 3 \times 10^{-5}$. Note that due to the 4-loop suppression of $d_e(J)$, the largest CKM contribution to paramagnetic atoms and molecules may come from nuclear and semileptonic operators. These results are all well below current experimental sensitivity. In addition, Majorana phases in the right-handed neutrino sector induce further suppressed contributions to lepton EDMs at 2-loop order, of the form $|d_e| \sim m_e m_\nu^2 G_F^2 < 10^{-43} e\,{\rm cm}$ [0] for a generic seesaw.

***CP*-odd new physics in the LHC era** :
Supersymmetry (SUSY) has for some time been the prevailing theoretical framework for weak-scale physics beyond the SM, motivated by its ability to remove the tuning apparent in the hierarchy between the weak scale and the Planck scale. The LHC has yet to discover any new electroweak scale physics, and thus viable SUSY models are now constrained. In particular, for most scenarios the masses of the superpartners of the first generation quarks (up and down squarks) must be well above a TeV. This conclusion has been hinted at by indirect constraints for many years. Indeed, as most SUSY models introduce a number of new CP-violating phases, EDMs have imposed strong constraints on the masses of these squarks assuming the phases are $\mathcal{O}(1)$ - the so-called SUSY CP problem. It is now becoming clear that this tension was indeed a sign that these mass limits were genuine. The situation is summarized rather schematically in Fig. 2, for a simple setup with two new phases θ_μ and θ_A.

These constraints depend on the details of the SUSY spectrum. Very schematically, we can write SUSY contributions to quark and lepton EDMs in the form,

$$d_f \sim d_f^{1-{\rm loop}}(m_{\rm gaugino}, m_{\rm f-squark}) + d_f^{2-{\rm loop}}(m_{\rm Higgses}, m_{\rm stop}) + \cdots \tag{13}$$

The 1-loop contributions can be suppressed below current sensitivity levels by raising the mass of some of the first-generation superpartners as in Fig 2. At this point, several generically subleading, but more robust, 2-loop contributions (e.g. [0]) and four-fermion interactions become important. These depend instead on masses associated with the SUSY Higgs sector and particles such as the stop which have large couplings to this sector. Since these parameters are tied to SUSY's stabilization of the Higgs mass, they should not be too large if SUSY is to play any role at the electroweak scale. These contributions are currently at the threshold of detection, and in some cases already being probed by the Hg EDM limit. Many similar 2-loop contributions to EDMs arise in varied models of extended Higgs sectors, or other means of stabilizing the Higgs mass. With the recent LHC discovery of a Higgs-like particle at ~ 125 GeV, this bodes well for the ability of the next generation of EDM searches to have a useful interplay with the LHC's exploration of new physics at the electroweak scale and above.

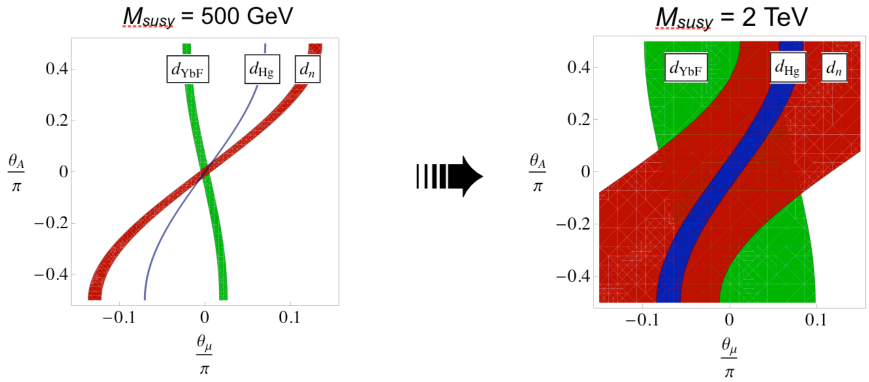

Fig. 2 Constraints on the (constrained) MSSM phases θ_A and θ_μ from the combined EDM limits (intersection of the bands), using two generic SUSY mass scales and $\tan\beta = 3$ for illustration. On the left, $M_{\rm SUSY} = 500$ GeV which is now excluded by the LHC, and on the right $M_{\rm SUSY} = 2$ TeV.

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