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Theory of electric dipole moments and lepton flavour violation

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Electric dipole moments and charged-lepton flavour-violating processes are extremely sensitive probes for new physics, complementary to direct searches as well as flavour-changing processes in the quark sector. Beyond the "smoking-gun" feature of a potential significant measurement, however, it is crucial to understand their implications for new physics models quantitatively. The corresponding multi-scale problem of relating the existing high-precision measurements to fundamental parameters can be approached model-independently to a large extent; however, care must be taken to include the uncertainties from especially nuclear and QCD calculations properly.

16th International Conference on B-Physics at Frontier Machines
2-6 May 2016
Marseille, France

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1. Introduction

Electric dipole moments (EDMs) and charged-lepton flavour-violating (cLFV) processes provide competitive means to search for new physics (NP), complementary to strategies like direct searches at hadron colliders, but also to other indirect searches like the flavour-changing processes investigated at the flavour factories. The exceptional sensitivity is due to the combination of experimental precision with a tiny Standard Model (SM) background. The smallness of the latter is related to the very specific connection between flavour and CP violation in the SM,[1] embodied by the Kobayashi-Maskawa mechanism [1], which is very effective in suppressing flavour-changing neutral currents (FCNCs) in the quark sector [2], much more so in in the lepton sector, but also flavour-conserving neutral currents involving CP violation.[2] The remaining SM contributions are many orders of magnitude below the present limits, *e.g.* $d_n^{\rm SM,CKM} \lesssim 10^{-(31-32)}\, e\,{\rm cm}$ [4, 5, 6, 7] for the neutron EDM. The observation of an EDM or cLFV with the present experimental precision would therefore clearly constitute a NP signal.

2. EDMs

Sakharov's conditions [8] require the presence of new sources of CP violation to explain the observed baryon asymmetry of the universe; while this does not *imply* sizable EDMs, they are generally very sensitive to such sources. In fact, generic NP scenarios usually yield contributions that are large compared to experimental limits, implying either a high NP scale or a very specific structure for additional CP-violating contributions, similar to the situation in the flavour-changing sector. Casting these qualitative statements into reliable bounds on model parameters requires knowledge of their relation to the experimental observables – typically (bounds on) frequency shifts obtained for composite systems. The calculation of these relations proceeds via a series of effective field theories (EFTs), see *e.g.* Refs. [9, 10, 11, 12] for recent reviews and references therein. Importantly, this approach allows to perform a large part of the analysis model-independently. The calculation of the matrix elements of the corresponding effective operators often include large uncertainties which have to be taken into account, see Refs. [12, 13] for recent detailed discussions. Furthermore, in composite systems different contributions can exhibit cancellations; this issue can already be systematically addressed for paramagnetic systems [14, 15], and in the future potentially also for diamagnetic ones [16].

2.1 Model-independent constraints from EDM measurements

The available competitive observables, that is, the EDMs of thorium monoxide (ThO) and ytterbium fluoride (YbF) molecules [17, 18], thallium (Tl) and mercury (Hg) atoms [19, 20, 21] and the neutron [22, 23] (see also [24]), are related by calculations on the molecular, atomic,

[1] EDMs are T,P-odd; their existence implies also CP violation when assuming CPT to be conserved as we will in this article.

[2] An exception to the latter statement is provided by the gluonic operator $\mathscr{O}_{G\tilde{G}} \propto \varepsilon_{\mu\nu\rho\sigma} G^{\mu\nu} G^{\rho\sigma}$, yielding a potentially very large contribution to hadronic EDMs which is, however, strongly bounded experimentally, constituting the *strong CP problem*. In the following it is assumed that this issue is resolved by the Peccei-Quinn- or a similar mechanism [3].

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nuclear and QCD levels to the coefficients of an EFT at a hadronic scale (see, *e.g.*, Refs. [10, 12, 25]). The operator basis consists of (colour-)EDM operators $\mathscr{O}_f^{\gamma,C}$, the purely gluonic Weinberg operator $\mathscr{O}_W$ and T- and P-violating four-fermion operators $\mathscr{O}_{ff'}$ without derivatives ($f^{(\prime)} = e, q$, $q = u, d, s$). Since these calculations do not depend on the NP model under consideration, this Lagrangian is used as the interface between experiment and high-energy calculations: the latter provide the model-specific expressions for the corresponding Wilson coefficients , with at least one more intermediate EFT at the electroweak scale.

In neutral composite systems, the EDMs of the components are shielded; for non-relativistic, point-like constituents this shielding is perfect, therefore measurements for this type of system rely on the violation of these assumptions [26]. For paramagnetic systems, relativistic effects can actually lead to *enhancement* factors, if the proton number Z is large enough [27, 28, 29], since two contributions scale approximately with Z^3: these are the ones from the electron EDM and the scalar electron-nucleon coupling, $\tilde{C}_S$.[3] Heavy paramagnetic systems can therefore be assumed to be completely dominated by these two contributions, allowing a model-independent fit to bound and eventually determine *both* contributions, without the assumption of a vanishing electron-nucleon contribution [14, 15]. In practice, there are two complications with this approach at present, which can however be overcome with additional measurements. Firstly, the ratio of the coefficients of the two contributions is necessarily similar for heavy paramagnetic systems [14]. This problem can be solved by performing measurements with atoms or molecules with largely different proton numbers, such as rubidium and francium atoms. Lacking such (competitive) measurements, it is possible to assume *e.g.* the limit from Hg to be saturated by the $d_e, \tilde{C}_S$ contributions [15]:[4] this is a conservative procedure, since the EDM of this system is typically dominated by colour-EDM (cEDM) contributions; the coefficients of the $d_e, \tilde{C}_S$ contributions in Mercury are about a factor 10^8 smaller than in paramagnetic molecules. We illustrate this procedure in Fig. 1 (left); the fit yields

$$d_e \leq 2.7\,10^{-28} e\,\mathrm{cm}\,(95\%\ \mathrm{CL})\,, \quad \text{and} \quad \tilde{C}_S \leq 1.5 \times 10^{-8}\,. \tag{2.1}$$

These values should be used when extracting bounds on parameters from d_e in any model in which the electron-nucleon contribution cannot be argued to be negligible. Furthermore, this 2-dimensional constraint allows to obtain model-independent limits on the EDMs of all other heavy paramagnetic systems [15]. A significant measurement in one of these systems larger than these bounds would indicate an experimental problem. These limits are orders of magnitude below existing experimental ones. Importantly, present experiments aim at an even better sensitivity [31, 32, 33, 34, 35], as illustrated on the right-hand side in Fig. 1.

The extension of this type of fit to all EDM measurements is clearly possible and has been proposed in Ref. [16]. While this is complicated by the many potential contributions – all of the terms mentioned above are relevant in general, this should be aimed for in the future. Since model-independent bounds/determinations are necessary to determine the specific structure of CP-violating NP contributions – and thereby potentially the model itself –, it is essential to have as many measurements in different systems as possible. An additional complication for the EDMs

[3]Note that $\tilde{C}_S$ depends in general on the considered system. However, for the systems at hand (and more generally for heavy paramagnetic systems), it is universal to very good approximation [15].

[4]Note that we include here the contribution of d_e as well, although its coefficient is very uncertain [30]. We allow for a factor of 2 in this estimate, which is however an arbitrary choice. Additional calculations are necessary.

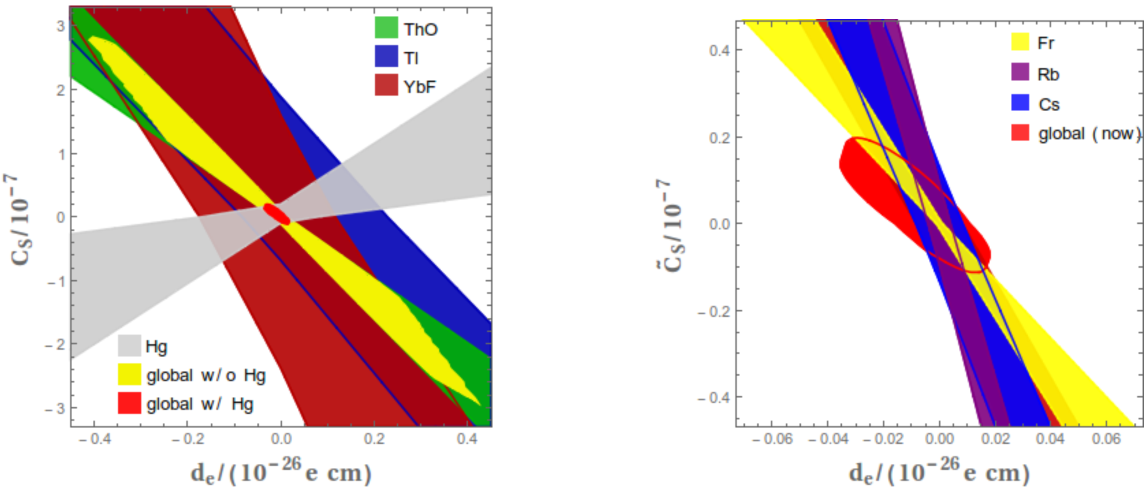

Figure 1: Fit to the recent measurements for paramagnetic systems [17, 18, 19], using additionally the Hg measurement [21] (grey band on the left). These plots are updated versions of the ones in Refs. [13, 15].

of diamagnetic systems and neutrons is that the theoretical uncertainties for the relevant matrix elements are often large and can in some cases preclude the extraction of conservative limits, for instance on the cEDMs from Hg [13], highlighting the importance of additional theoretical studies, but also further motivating complementary measurements.

2.2 NP contributions to EDMs

Reliable limits on parameters in NP models from EDMs are difficult to achieve. Reasons are, apart from the fact discussed previously that presently less competetive measurements than relevant effective operators exist, the presence of several contributions to each of these coefficients and the various relevant hierarchies, *i.e.* in mass scales, couplings and loop factors. This complicates semi-model-independent analyses for classes of models and allows strict statements only under additional assumptions. However, once a specific model is considered, typically strong correlations exist between EDMs and other CP-violating observables.

Generic NP contributions at tree- and one-loop level are in conflict with the stringent experimental limits. On the two-loop level, usually so-called Barr-Zee- and Weinberg diagrams dominate [36, 37, 38], which compensate the additional loop factor by avoiding small mass factors. However, flavour sectors are usually far from generic; therefore in some cases also tree-level diagrams can be relevant, for example when they involve small mass factors, see below.

In order to demonstrate these qualitative statements in a specific model, we consider a general two-Higgs-doublet model (2HDM). In this setup, the situation is typically the one described above: four-quark (tree-level) contributions are subleading, one-loop contributions to (colour-)EDMs are under control (but not necessarily tiny), and two-loop contributions are dominant, but also the tree-level quark-electron couplings are relevant, despite the small mass factors [39, 13]. To be (even more) specific and able to relate the resulting bounds quantitatively to those from other observables, we will furthermore consider the Aligned 2HDM (A2HDM) [40, 41], where the Yukawa matrices in each sector are proportional to each other in order to avoid FCNCs at tree-level, but with complex proportionality factors.

The electron EDM receives in this class of models contributions mostly from Barr-Zee diagrams; the resulting constraints require factors at the percent level in addition to the suppression by fermion masses and CKM factors, questioning already the common assumption that such factors should be $\mathscr{O}(1)$. In the A2HDM this can be compared to the absolute value of the same parameter combination obtained from leptonic and semileptonic decays [41, 42], which is about a factor 1000 weaker, demonstrating again the sensitivity of EDMs to CP-violating parameters.

As mentioned above, also the constraint from $\tilde{C}_S$ is relevant: while in this case the constraint is numerically weaker, it is again at least a factor 100 stronger than an analogous constraint from (semi-)leptonic processes in the A2HDM [41, 42].

For the neutron, the constraint induced in the charged-Higgs sector via the Weinberg operator is the dominant one. While this constraint does not imply sizable fine-tuning yet, it already prohibits large CP-violating effects in other observables in specific models. For instance, while the indirect constraint from the branching ratio in $b \to s\gamma$ in the A2HDM still allows for a sizable CP asymmetry for this process, a NP contribution of $|A_{\rm CP}(b \to s\gamma)| \lesssim 1\%$ follows from the EDM bound and the discussion in Refs. [43, 44].

These examples show the potential of EDMs, but also their complementarity to other searches, since only the imaginary parts of parameter combinations are constrained. However, for the combinations EDMs are sensitive to, they are often the strongest constraints available.

3. cLFV

Since lepton-flavour violation has been observed in neutrino oscillations, it should be present for charged leptons as well, even within the SM. While the corresponding predictions are complicated by the fact that the neutrino sector is not fully specified, minimal extensions yield typically tiny predictions for cLFV, $\sim \Delta m_\nu^2/M_W^2 \sim 10^{-25}$ in the amplitude, due to the GIM mechanism [2], way below anything we can hope to detect in the foreseeable future.[5]

Generic NP contributions can be many orders of magnitude larger, rendering cLFV observables excellent observatories for NP searches. With a generic NP contribution suppressed by $1/M^2$, where M is a mass scale characterizing the new contributions, the rate for cLFV processes is simply suppressed by the square of this factor, $1/M^4$, implying that a given limit has to be improved by four orders of magnitude in order to gain one order on the mass scale of NP. This is in contrast to the case of EDMs which constitute an interference effect and therefore suffer only once from the strong suppression.

As for EDMs, the low-energy description can be almost model-independently performed in the context of EFTs. However, similarly to EDMs the analysis is complicated by the fact that the mass hierarchy is not necessarily the dominating one, given the involvement of various small quantities. We concentrate here on the case of lepton-number conservation, *i.e.* $\sum \Delta L_i = 0$. The leading $|\Delta L_i| = 1$ operators are then radiative operators (mediating *e.g.* $\mu \to e\gamma$), purely leptonic operators (mediating *e.g.* $\mu \to e\bar{e}e$), and semi-leptonic operators (mediating *e.g.* $\mu \to e\bar{q}q$). At the electroweak scale, there are furthermore operators containing Higgs- and heavy gauge-boson fields

[5] Note that the fact that with only one neutrino $\mu \to e\gamma$ would occur at a rate inconstistent with other weak transitions has been observed much earlier [45], although without proposing the GIM cancellation as the solution.

explicitly, discussed elsewhere at this conference [46, 47]. Experimentally, the three low-energy classes of operators have each their experimental equivalent in the sense that there are observables they contribute to on tree-level: obviously $\ell \to \ell'\gamma$ and $\ell \to \ell'\bar{\ell}'\ell''$, and for $\ell \to \ell'\bar{q}q$ (semi-)leptonic decays of mesons and $\mu \to e$ conversion in heavy atoms. On the loop-level, this simple correspondence ceases to exist. Nevertheless, again similarly to EDMs, the hierarchy between these different classes and within different conversion processes can be used to pin down the operators responsible once cLFV processes are observed, which in turn helps to identify the NP model responsible, see *e.g.* Refs. [48, 49, 50]. This observation implies that there is no single "best" measurement, but that as many measurements as possible should be performed, for different transitions.

The existing experimental bounds are strongest for transitions between muons and electrons by far, at least numerically: most recently, the MEG collaboration obtained the limit $BR(\mu^+ \to e^+\gamma) \leq 4.2 \times 10^{-13}$ [51], while the limits on $\mu \to e\bar{e}e$ and muon-electron conversion stem from the SINDRUM(II) collaborations. Significant improvements are expected from ongoing and coming experiments, see the presentaions [52, 53, 54]. LFV processes involving the τ lepton are much less constrained; while in some models large effects can be excluded from the bounds on $\mu \to e$ transitions, this clearly depends on the specific flavour structure of the model. On the other hand, effects involving the τ could be enhanced, motivated by its larger mass, its being part of the third generation, and also the presently observed 4σ-hint of lepton-flavour non-universality (LFNU) involving $b \to c\tau\nu$ transitions. In fact, LFNU generically also yields LFV, see *e.g.* Refs. [55, 56], due to the rotation to the mass basis. This yields additional motivation to search for LFV decays of B mesons. However, "typically" does not mean "necessarily"; exceptions have for instance been discussed in Refs. [57, 58].

4. Conclusions

EDMs and cLFV processes provide unique constraints for the CP- and lepton-flavour-violating sectors of NP models, respectively. A potential discovery of any such process would be a major achievement, independent of its source. The interpretation of bounds and potential measurements in terms of fundamental theory parameters requires the careful estimation of theoretical uncertainties and is complicated by potential cancellations on various levels. While this problem can be addressed for the EDMs of heavy paramagnetic systems to extract the electron EDM and scalar electron-nucleon coupling model-independently, a similar approach including all relevant systems should be aimed at, but requires several additional measurements for different systems.

For the occuring combinations of parameters, EDMs typically provide the most stringent constraints. We demonstrated this explicitly for general 2HDMs, and more specifically for the A2HDM, where large CP-violating effects in other observables are strongly bounded by the existing EDM limits.

cLFV processes have a long history of excluding NP models, imposing very stringent bounds on any model that exhibits LFV. Again it is crucial to search in as many channels as possible, as only the combination of many observables can yield information on the underlying model. The recent hints at LFNU motivate additionally the search for LFV B meson decays, however, there is no guarantee, since models can exhibit LFNU without inducing LFV.

Given the present strength of these constraints, forthcoming experiments will test a crucial part of the parameter space and might turn existing bounds into observations.

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