The neutron EDM vs up and charm flavour violation

Filippo Sala

Institut de Physique Théorique, CNRS and CEA/Saclay, F-91191 Gif-sur-Yvette, France

We derive a strong bound on the chromo-electric dipole moment of the charm quark, and we quantify its impact on models that allow for a sizeable flavour violation in the up quark sector. In particular, we show how the constraints coming from the charm and up CEDMs limit the size of new physics contributions to direct flavour violation in \( D \) decays. We also specialize our analysis to the cases of split-families Supersymmetry and composite Higgs models. The results we expose motivate an increase in experimental sensitivity to fundamental hadronic dipoles, and a further exploration of the SM contribution to both flavour violating \( D \) decays and nuclear electric dipole moments.

1 Introduction and motivation

The Cabibbo Kobayashi Maskawa (CKM) picture of flavour and CP violation in the quark sector has successfully predicted all the related experimental results to date. The high level of precision to which it has been tested can be quantified by parameterising new physics (NP) via the effective Lagrangian

\[
\mathcal{L}_{\text{NP}} = \sum_i \frac{c_i}{\Lambda_i} \mathcal{O}_i, \tag{1}
\]

where \( \mathcal{O}_i \) are flavour violating (FV) operators of dimension six, that describe the effect of new degrees of freedom appearing roughly at the scale \( \Lambda_i \). If one assumes the coefficients \( c_i \) to be of order one, as expected for a generic NP model, then the bounds on such scales \( \Lambda_i \) can reach values of \( 10^{4÷5} \) TeV, depending on the operator under consideration. Any theory that requires the existence of new states below these values has to face this issue, which is often referred to as the “NP flavour problem”. In particular, such high scales are unacceptable for models that aim at addressing the hierarchy problem in a natural way, since by construction their new scale is as close as possible to the electroweak (EW) one. Actually these models strictly require only the NP scale associated with the third generation to be close to the Fermi one, while the scale associated with the first two generations could be well above it. This separation is indeed a welcome property for natural models in light of collider constraints.

A possible way to address the NP flavour problem is to give the theory a specific feature, like a flavour symmetry or some dynamical property, that makes all the desired coefficients \( c_i \) small.
enough. In doing so, it can be useful to keep in mind that the higher energy scales in eq. (1) are probed by operators involving down quarks, strongly constrained by measurement of decay properties of $K$ and $B$ mesons. On the contrary, constraints from the up-quark sector probe lower scales. Despite this, it is not difficult to build models where flavour violation in the up sector is in the ballpark of current experimental sensitivities, like for example flavour alignment

1, composite Higgs models with an anarchic flavour structure, and Generic $U(2)^3$.

In light of the previous discussion, it is interesting to look for indirect experimental signatures of a class of models defined by i) NP scale of the third generation below the one of the first two, and ii) largish FV effects in the up quark sector. Within this framework, operators of particular interest are the dipoles

$$\mathcal{L}_{\text{NP}} \supset c_{ij} \frac{m_t}{\Lambda^2} (\bar{u}_L i \sigma_{\mu \nu} T^a u_R) g_s G_{\mu \nu}^a ,$$

where $i, j = u, c$. The strongest experimental probes of the associated energy scale are, currently, direct CP asymmetries in $D$ meson decays$^3$, $A_{CP}$, and the neutron EDM $d_n$. The former are sensitive to $c_{uc}$ and $c_{cu}$, and the latter to $c_{uu}$, cause $c_{uu}$ is directly proportional to the chromo-EDM of the up quark. Property i) of our class of models implies the relation

$$c_{uu} c_{cc} = c_{uc} c_{cu}, \quad (3)$$

so that one can have a largish contribution to $A_{CP}$ and respect at the same time the $d_n$ bound, by taking a large enough $c_{cc}$.

In this contribution, which is based on$^4$, we will show that the neutron EDM is actually sensitive to $c_{cc}$. The constraint we will derive, despite being a first bound on the charm chromo-EDM, has important phenomenological consequences for all models satisfying eq.(3): the bound from $d_n$ challenges the possibility to observe an asymmetry $A_{CP}$. This conclusion will be remarkably strengthened by the expected future progresses, as we will now explain. The current upper bound on the neutron EDM reads$^5$ $d_n < 2.9 \times 10^{-26} e \text{ cm} \ (90\% \text{ CL})$, and the foreseen experimental sensitivity is at the level of $10^{-28} e \text{ cm}$, and is aimed at by many experimental collaborations (see e.g. section 7 of$^6$ and references therein). Such a value is a genuine probe of new physics, since the SM contribution is estimated to be at the level of $10^{-31} e \text{ cm}$. The stronger constraint on CPV decays of the $D$ meson comes from the LHCb measurement$^8$ of the difference $\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$, whose world average$^9$ is $(-3.29 \pm 1.21) \times 10^{-3}$. The SM prediction for such decays is at the level of a few$\times 10^{-3}$, and is plagued by long distance uncertainties that are still a source of discussion in the community$^{10,11,12,13}$.

In the rest of this contribution we will derive the bound in section 2, and analyse quantitatively its phenomenological implications in section 3. A critical summary and an outlook will be provided in section 4.

2 Bound on the chromo-EDM of the charm quark

The expression of the neutron EDM in terms of fundamental quantities, if a Pececi-Quinn symmetry is assumed to get rid of the $\theta_{QCD}$ term, reads$^{14}$

$$d_n = (1 \pm 0.5)[1.4(d_d - 0.25d_u) + 1.1e(\bar{d}_d + 0.5\bar{d}_u)] \pm (22 \pm 10)e \text{ MeV} \ w , \quad (4)$$

where $d_{u,d}$ and $\bar{d}_{u,d}$ are the EDM and CEDM of the up and down quarks, and $w$ is the coefficient of the three-gluon Weinberg operator. They are defined via the effective Lagrangian$^a$

$$\mathcal{L}_{\text{eff}} = d_q \frac{1}{2} (\bar{q} \sigma_{\mu \nu} i \gamma_5 q) F_{\mu \nu} + \bar{d}_q \frac{1}{2} (\bar{q} \sigma_{\mu \nu} T^a i \gamma_5 q) g_s G_{\mu \nu}^a + w \frac{1}{6} f_{abc} \epsilon^{\mu \nu \lambda \rho} G_{\mu \sigma}^a G_{\nu \rho}^b \sigma G_{\lambda}^c , \quad (5)$$

where $q = u, d, s, c, b, t$ and $\epsilon^{0123} = 1$. Every time we will employ the $d_q$ bound to constrain the size of new physics, we will conservatively use the values 0.5 and 12 MeV for the coefficients $1 \pm 0.5$ and $22 \pm 10$ MeV in (4).

$^a$With the definition of the effective operator in (2), one has $\bar{d}_q = 2 (m_t/\Lambda^2) \text{Im} (c_{qq})$. 
The quarks EDMs and CEDMs do not mix in the Weinberg operator via renormalisation group evolution, however they nonetheless give a contribution to $w$. In fact, when in the running from high to low energies a heavy quark is integrated out, its CEDM gives a threshold correction to the Weinberg operator that reads\textsuperscript{15,16,17}

$$w = \frac{g_s^3}{32\pi^2 m_q} \tilde{q},$$

(6)

where all the parameters are evaluated at the mass of the quark $q$. Expression (6) is the one-loop result, the uncertainty coming from higher loops can be estimated to be at the level of $8\alpha_s(m_q)/4\pi (= 25\%$ for $q = c$), where 8 is a colour factor. The subsequent running from $m_q$ makes also the lighter quarks dipole moments sensitive to $\tilde{q}$. For the charm quark, the impact of $\tilde{c}_c$ in $d_n$ is mainly driven by its contribution to $w$, which dominates over the light quark dipole moments by roughly two order of magnitudes. Using the threshold contribution (6) and the one-loop running from\textsuperscript{18,19}, one can write the expression

$$d_n = d_n(d) \pm d_n(w), \quad d_n(d) = (1 \pm 0.5)(4.9 \times 10^{-6} c \tilde{d}_c), \quad d_n(w) = (1 \pm 0.45)(5.1 \times 10^{-4} c \tilde{d}_c),$$

(7)

where $\tilde{d}_c$ is evaluated at the charm mass scale. The upper limit $d_n < 2.9 \times 10^{-26}$ then implies

$$|\tilde{d}_c| < 1.0 \times 10^{-22} \text{cm},$$

(8)

or, equivalently, $m_c|\tilde{d}_c| < 6.7 \times 10^{-9}$. The bound is derived considering only the charm dipole contribution to $d_n$. An analysis analogous to the one we performed here can be carried out also for the bottom and top CEDMs, as was done in\textsuperscript{20} and\textsuperscript{21}. We give here the bounds one obtains in this way for the heavy quarks, in terms of the coefficients of operators analogous to (2)

$$\text{Im}(c_{uu}) < 1.3 \times 10^{-8}, \quad \text{Im}(c_{cc}) < 1.8 \times 10^{-5},$$

(9)

$$\text{Im}(c_{dd}) < 8.4 \times 10^{-9}, \quad \text{Im}(c_{bb}) < 1.7 \times 10^{-4},$$

(10)

$$\text{Im}(c_{tt}) < 3.3 \times 10^{-2},$$

(11)

where all the coefficients are evaluated at the scale $\Lambda = 1$ TeV, and we have shown the $d_n$ bounds on the lighter quarks CEDMs for comparison.

### 3 Implications for new physics

As discussed in section 1, the current and foreseen experimental reach in $d_n$ will impact, thanks to the bound we derived, on the flavour violating phenomenology of new physics. More specifically we consider CP violating $D$ meson decays, for which the current measurement of $\Delta A_{CP}$ implies $\text{Im}(c_{u,c,u}) < 3.8 \times 10^{-6} \times (\Lambda/\text{TeV})^2$. This bound is plagued by $O(1)$ long-distance uncertainties of the matrix elements of the dipole operators.

Property i) of the class of models under considerations makes it convenient to rewrite the coefficients of (2) as

$$c_{ij} = e W_{i3}^L W_{3j}^R,$$

(12)

where the quantities $W_{i3}^L, W_{k3}^R$ quantify the communication of the $k$th generation of quarks with the new physics states associated with the third generation. Many NP models of flavour realise $W_{i3}^L \simeq V_{i3}^{\text{CKM}}$, since as we discussed flavour violation in the down quark sector has to be kept under control. With this assumption for the size of $W^L$, the bounds from $d_n$ and $\Delta A_{CP}$ imply

$$\Delta A_{CP} : \quad |W_{3u}^R| < 1.1 \times 10^{-3}, \quad |W_{3u}^R| < 9.2 \times 10^{-5},$$

(13)

$$d_n : \quad |W_{3c}^R| < 4.4 \times 10^{-4}, \quad |W_{3u}^R| < 3.7 \times 10^{-6},$$

(14)

where we have chosen a NP scale $\Lambda = 1$ TeV, and considered one operator at a time. Without taking into account the contributions from the charm CEDM, one could have saturated the
ΔACP measured value without being in conflict with the EDMs constraints, via requiring a very small $W^R_{3u}$, see e.g. 22. Now this possibility is challenged and, with the foreseen experimental sensitivities, in these models the neutron EDM will become by far the most powerful observable to probe the flavour violating parameters $c_{uc,cu}$. We stress that all these bounds should be considered as $O(1)$ limits, barring fine-tunings of the unknown coefficients and overall phases in front of the operators, that could potentially affect the above conclusion.

Supersymmetry with split families 23,24,25 is an explicit realisation of the situation described above. The contributions to the coefficients of eq. (2) are dominated by those from gluino-stop loops, which read

$$c_{ij} \frac{A_t - \mu \cot \beta}{4\pi m^2_{\tilde{g}}} \frac{5}{36} g_8(x_{gt}) W^L_{i3} W^R_{j3},$$

where now $W^{L,R}$ are the mixing matrices entering the gluino-quark-squark vertices of respective chirality, which are responsible for the flavour violation, and $g_8$ is a loop function ($g_8(1) = 1$). It turns out that in split-families SUSY, under some motivated assumptions, one can derive more robust bounds with respect to those analogous to (13). In fact one can drop the hypothesis of switching on one operator at a time at the high scale, and instead consider all the leading contributions to $d_n$ at once. To do so it is sufficient to add, to the up and charm CEDMs, only the up quark EDM $d_u$. This does not introduce new parameters, since its form will be analogous to (15), with the only change of $g_8$. In fact the top and bottom CEDMs contributions are subleading by more than one order of magnitude, once the appropriate Yukawa and mixing suppressions are taken into account. Moreover it is reasonable to assume that also the down quark EDMs contribution can be neglected: not only they receive a further $y_t/y_b$ suppression with respect to the up and charm ones, but the relevant mixing matrices enter the $\epsilon_K$ parameter, which constrains them to be much smaller than the corresponding ones in the up quark sector, if stops and sbottoms have similar masses. Note finally that we neglect the contribution to $d_n$ that would come from CP violation in the gaugino and Higgs sectors, which is very strongly constrained by the bound on the electron EDM 26. The bounds from $d_n$ and $\Delta A_{CP}$ derived in this way are shown in Figure 1 in the $|W^R_{ic}|-|W^R_{fu}|$ plane, for $m_{\tilde{g}} = 2 m_\ell = 1.5$ TeV and $(A_t - \mu/\tan \beta)/m_\ell = 1$. For illustrative purposes we have assumed the elements of $W^L$ to be equal in magnitude to the respective CKM ones and all the phases to be maximal.

Another interesting picture where to study the impact of this bound is the one of composite Higgs models 27,28,29,30 with partial compositeness 31, as a concrete realisation of a dynamical suppression of flavour violation. The careful analysis of 32 shows that, thanks to the new bound on $d_c$, it is the neutron EDM that gives the stronger constraints on the masses of the composite partners of the up quarks. For more details on both this case and the SUSY one see 4.

4 Summary and outlook

We have derived a bound on the charm chromo-electric dipole moment $d_c$, via its threshold effect in the three gluon Weinberg operator $w$. This operator in turn contributes to hadronic dipole moments, and the $d_c$ bound yields to $d_c < 1.0 \times 10^{-22}$ cm at 90% C.L. at the charm mass scale. If one had neglected the impact of $w$ to $d_n$, the resulting bound would have been $|d_c| < 1.2 \times 10^{-20}$ cm, coming from the $d_c$ contribution to the light quarks CEDMs. This stresses the importance of reducing the theory uncertainty of the $w$ contribution to hadronic EDMs, whose size is at present debated 33. Another theoretical progress, that is further motivated by this result, is the determination of the long-distance contribution of the charm EDMs to $d_n$.

We also pointed out the relevance of this bound for models allowing for a non-negligible flavour violation in the up quarks sector. These models are still largely unconstrained due to the weakness of the flavour and CP violating bounds compared to those for the down-quark sector. Before this work, the CP asymmetry in flavour violating $D$ decays, $\Delta A_{CP}$, was setting the stronger constraints on some relevant flavour violating parameters in these models. We
Figure 1 – The lines represent the experimental sensitivities to the flavour violating matrix elements in split-families SUSY, the shaded regions are currently excluded. Dashed: current neutron EDM. Dotted: projected neutron EDM. Continuous: Direct CP asymmetry in $D$ decays.

found that the current bound on $d_n$ is already slightly more constraining than $\Delta A_{\text{CP}}$. More importantly, the lack of a theoretical understanding of the SM contribution to $\Delta A_{\text{CP}}$, combined with the expected improvement in experimental sensitivity to $d_n$, will make the neutron EDM the most sensitive probe for these flavour violating parameters, strengthening the current bounds by more than two orders of magnitude. This conclusion would be improved by a further order of magnitude if the deuteron EDM will be measured with a precision of $\sim 10^{-29} e\text{cm}$, which is the value aimed at by the proposal. This interplay of $d_n$ and flavour violating observables constitutes an additional motivation to achieve a better theoretical control of direct CP violations in $D$ decays.

Acknowledgments

I thank the organisers of MoriondEW 2014 for the enjoyable ambience created in La Thuile, as well as for partial support and for the opportunity to give this talk. I thank Michele Papucci for many precious discussions about these subjects. The participation to this conference was also supported by the European Research Council (ERC) under the EU Seventh Framework Programme (FP7/2007-2013) / ErC Starting Grant (agreement n. 278234 - NewDark project).

References

1. Yosef Nir and Nathan Seiberg. Should squarks be degenerate? Phys.Lett., B309:337–343, 1993.
2. Riccardo Barbieri, Dario Buttazzo, Filippo Sala, and David M. Straub. Less Minimal Flavour Violation. JHEP, 1210:040, 2012.
3. Gino Isidori, Jernej F. Kamenik, Zoltan Ligeti, and Gilad Perez. Implications of the LHCb Evidence for Charm CP Violation. Phys.Lett., B711:46–51, 2012.
4. Filippo Sala. A bound on the charm chromo-EDM and its implications. JHEP, 1403:061, 2014.
5. C.A. Baker, D.D. Doyle, P. Geltenbort, K. Green, M.G.D. van der Grinten, et al. An Improved experimental limit on the electric dipole moment of the neutron. Phys.Rev.Lett., 97:131801, 2006.
6. J.L. Hewett, H. Weerts, R. Brock, J.N. Butler, B.C.K. Casey, et al. Fundamental Physics at the Intensity Frontier. arXiv:1205.2671, 2012.
7. Thomas Mannel and Nikolai Uraltsev. Loop-Less Electric Dipole Moment of the Nucleon in the Standard Model. *Phys.Rev.*, D85:096002, 2012.

8. R Aaij et al. Search for direct CP violation in $D^0 \rightarrow h^- h^+$ modes using semileptonic $B$ decays. *Phys.Lett.*, B723:33–43, 2013.

9. Y. Amhis et al. Averages of B-Hadron, C-Hadron, and tau-lepton properties as of early 2012. 2012. Online update at http://www.slac.stanford.edu/xorg/hfag.

10. David Pirtskhalava and Patipan Uttayarat. CP Violation and Flavor SU(3) Breaking in D-meson Decays. *Phys.Lett.*, B712:81–86, 2012.

11. Hai-Yang Cheng and Cheng-Wei Chiang. Direct CP violation in two-body hadronic charmed meson decays. *Phys.Rev.*, D85:034036, 2012.

12. Joachim Brod, Yuval Grossman, Alexander L. Kagan, and Jure Zupan. A Consistent Picture for Large Penguins in $D \rightarrow p_i p_i^-, K^+ K^-$. *JHEP*, 1210:161, 2012.

13. Gino Isidori and Jerne F. Kamenik. Shedding light on CP violation in the charm system via D to V gamma decays. *Phys.Rev.Lett.*, 109:171801, 2012.

14. Maxim Pospelov and Adam Ritz. Neutron EDM from electric and chromoelectric dipole moments of quarks. *Phys.Rev.*, D63:073015, 2001.

15. Darwin Chang, Thomas W. Kephart, Wai-Yee Keung, and Tzu Chiang Yuan. The Chromoelectric dipole moment of the heavy quark and purely gluonic CP violating operators. *Phys.Rev.Lett.*, 68:439–442, 1992.

16. Geen Boyd, Arun K. Gupta, Sandip P. Trivedi, and Mark B. Wise. Effective Hamiltonian for the Electric Dipole Moment of the Neutron. *Phys.Lett.*, B241:584, 1990.

17. Michael Dine and Willy Fischler. Constraints on New Physics From Weinberg’s Analysis of the Neutron Electric Dipole Moment. *Phys.Lett.*, B242:239–244, 1990.

18. Eric Braaten, Chong-Sheng Li, and Tzu-Chiang Yuan. The Evolution of Weinberg’s Gluonic CP Violation Operator. *Phys.Rev.Lett.*, 64:1709, 1990.

19. Giuseppe Degrassi, Enrico Franco, Schedar Marchetti, and Luca Silvestrini. QCD corrections to the electric dipole moment of the neutron in the MSSM. *JHEP*, 0511:044, 2005.

20. D. Chang, Wai-Yee Keung, C.S. Li, and T.C. Yuan. QCD Corrections to CP Violation From Color Electric Dipole Moment of b Quark. *Phys.Lett.*, B241:589, 1990.

21. Jerne F. Kamenik, Michele Papucci, and Andreas Weiler. Constraining the dipole moments of the top quark. *Phys.Rev.*, D85:071501, 2012.

22. Gian Francesco Giudice, Gino Isidori, and Paride Paradisi. Direct CP violation in charm and flavor mixing beyond the SM. *JHEP*, 1204:060, 2012.

23. S. Dimopoulos and G.F. Giudice. Naturalness constraints in supersymmetric theories with nonuniversal soft terms. *Phys.Lett.*, B357:573–578, 1995.

24. Andrew G. Cohen, D.B. Kaplan, and A.E. Nelson. The More minimal supersymmetric standard model. *Phys.Rev.*, B388:598–598, 1996.

25. Michele Papucci, Joshua T. Ruderman, and Andreas Weiler. Natural SUSY Endures. *JHEP*, 1209:035, 2012.

26. Riccardo Barbieri, Dario Buttazzo, Filippo Sala, and David M. Straub. Flavour physics and flavour symmetries after the first LHC phase. arXiv:1402.6677, 2014.

27. David B. Kaplan and Howard Georgi. SU(2) x U(1) Breaking by Vacuum Misalignment. *Phys.Lett.*, B136:183, 1984.

28. Howard Georgi and David B. Kaplan. Composite Higgs and Custodial SU(2). *Phys.Lett.*, B145:216, 1984.

29. Roberto Contino, Yasunori Nomura, and Alex Pomarol. Higgs as a holographic pseudoGoldstone boson. *Nucl.Phys.*, B671:148–174, 2003.

30. Kaustubh Agashe, Roberto Contino, and Alex Pomarol. The Minimal composite Higgs model. *Nucl.Phys.*, B719:165–187, 2005.

31. David B. Kaplan. Flavor at SSC energies: A New mechanism for dynamically generated fermion masses. *Nucl.Phys.*, B365:259–278, 1991. Revised version.

32. Matthias Knig, Matthias Neubert, and David M. Straub. Dipole operator constraints on composite Higgs models. arXiv:1403.2756, 2014.

33. Jonathan Engel, Michael J. Ramsey-Musolf, and U. van Kolck. Electric Dipole Moments of Nucleons, Nuclei, and Atoms: The Standard Model and Beyond. *Prog.Part.Nucl.Phys.*, 71:21–74, 2013.

34. http://www.bnl.gov/edm/.