

Estimation of CP violating EDMs from known mechanisms in the SM *

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New sources of CP violation, beyond the known sources in the standard model (SM), are required to explain the baryon asymmetry of the universe. Measurement of a non-zero permanent electric dipole moment (EDM) in fundamental particles, such as in an electron or a neutron, or in nuclei or atoms, can help us gain a handle on the sources of CP violation, both in the SM and beyond. Multiple mechanisms within the SM can generate CP violating EDMs, *viz.* through the CKM matrix in the weak sector or through the QCD $\bar{\theta}$ parameter in the strong sector. We will estimate the maximum possible EDMs of leptons, certain baryons, select atoms and molecules in the $(\text{CKM} \oplus \bar{\theta})$ framework, assuming that the EDM wholly originates from either of the two SM mechanisms, independently. These estimates have been presented in light of the current experimental upper limits on the EDMs, in the following systems - leptons: e^- , μ^- , τ^- , ν_e^0 , ν_μ^0 , ν_τ^0 , baryons: n^0 , p^+ , Λ^0 , Σ^0 , Ξ^0 , Λ_c^+ , Ξ_c^+ , atoms: ^{85}Rb , ^{133}Cs , ^{210}Fr , ^{205}Tl , ^{199}Hg , ^{129}Xe , ^{225}Ra , ^{223}Rn , and molecules: HfF^+ , PbO , YbF , ThO , RaF , TlF . EDMs in different systems constrain CP-violating interactions differently *i.e.* the same measured constraint on the EDM in two different systems may not actually be equally constraining on CP violating parameters. Finally, we emphasize the need to measure a non-zero EDM in multiple systems before understanding the origins of these CP-violating EDMs.

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1. Introduction

A non-zero electric dipole moment (EDM) in sub-atomic particles indicates violation of parity (P), joint charge-parity (CP) and time reversal (T) symmetries [1]. CP violation is a required condition for baryogenesis in the early universe [2]. CP violation is a key ingredient of weak interactions, and in the quark sector of the SM it is encoded in the Cabbibo-Kobayashi-Maskawa (CKM) quark oscillation matrix [3, 4]. Note that since the mass differences of charged leptons is large, the oscillation between charged leptons is suppressed, but there is also CP violation encoded into the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix which describes the neutrino oscillations [5, 6], but we do not consider the contributions from the PMNS matrix in this paper. The amount of CP violation arising from the CKM matrix in the SM is insufficient to explain the observed baryon asymmetry of the universe [7]. CP violation could also be introduced into the strong sector of the SM, through the Quantum Chromodynamics (QCD)- $\bar{\theta}$ [8], but no CP violation has been observed in strong or electromagnetic interaction mediated processes.

In reality, the EDM of a system may arise from many sources: (i) the intrinsic EDM of the fundamental particles for leptons and quarks, (ii) CP violating pion-nucleon or nucleon-nucleon (both long range π NN-isoscalar and isovector, and short range hadronic) interactions, and (iii) CP violating electron-nuclear (both scalar and tensor) interactions. In a low energy paradigm, the EDM of a species has been expressed using the above terms in Ref. [9, 10, 11], which also provide a detailed review. While the CP violation in SM-CKM contributes to EDMs through all of the above mechanisms, the SM- $\bar{\theta}$ contributions enter through the isoscalar π NN and short range interactions. In this paper we will focus on reviewing and estimating the EDMs generated, by a single source, coming from either of two mechanisms in the SM, CKM or QCD- $\bar{\theta}$, and place them in light of the current experimental constraints. We have only considered systems where experimental constraints already exist or have been planned. Furthermore, we have neglected the sign of the EDM. In the next sections we will describe the process for estimation of EDMs in subatomic particles, in atoms, as well as in molecules. Finally, we have concluded with a short note discussing the short comings of these estimates.

2. EDM of sub-atomic particles

e^- : Diagrams that contribute to the EDM of charged leptons have four-loops [12]. This suppresses the SM-CKM mechanism generated electron EDM to $d_e^{(SM-CKM)} \sim 10^{-44}$ e-cm [12]. Ref. [13] has shown that electrons may also acquire an EDM through the SM- $\bar{\theta}$ of about $d_e^{(SM-\bar{\theta})} \sim 8.6 \times 10^{-38}$ e-cm. Using the polar molecule ThO, the ACME collaboration has set an experimental constraint of $d_e^{(90\% \text{ C.L.})} < 1.1 \times 10^{-29}$ e-cm [14].

μ^- (τ^-): The mechanisms that generate an EDM in muons (tau leptons) are identical to those in electrons. The EDM of charged leptons acquired through the two SM mechanisms scales with the inverse ratio of the masses [13]. Thus, we can scale up the SM-CKM and the SM- $\bar{\theta}$ EDMs of the electron by a factor of $m_{\mu^-}(\tau^-)/m_e$ to obtain the theoretical SM expectation for the muon (tau lepton) EDM. The experimental constraint for the muon (tau lepton) EDM, $d_{\mu^-}^{(90\% \text{ C.L.})} < 0.16(38) \times 10^{-18}$ e-cm, comes directly from the muon $g-2$ experiment [15] (comes from the Belle collaboration, using e^-e^+ collisions [16]). More recently, Ref. [17] has updated the limit to $d_{\tau^-}^{(90\% \text{ C.L.})} < 2.6 \times 10^{-18}$ e-cm using the above method.

ν^0 : The theoretical expectations for EDMs of neutrinos is as of yet unavailable. All the experimental constraints for neutrino EDMs come from indirect measurements involving $e\bar{e}$ collisions. The constraints of $d_{\nu_e^0}^{(90\% \text{ C.L.})} < 2 \times 10^{-21}$ e·cm and $d_{\nu_\mu^0}^{(90\% \text{ C.L.})} < 2 \times 10^{-21}$ e·cm have been reported in Refs. [18, 19]. Refs. [20, 21, 22] have reported a constraint of $d_{\nu_\tau^0}^{(90\% \text{ C.L.})} < 4.35 \times 10^{-17}$ e·cm.

n^0, p^+ : Diagrams that generate an EDM in baryons are simpler πNN diagrams with just one-loop [23], and consequently we can expect larger baryonic SM EDMs, compared to charged leptons. The neutron's SM-CKM EDM has been estimated to be around $d_n^{(\text{SM-CKM})} \sim 2 \times 10^{-32}$ e·cm [23]. The QCD- $\bar{\theta}$ parameter, in fact is directly proportional to the neutron EDM value [24]: $d_n \sim \bar{\theta} \cdot (6 \times 10^{-17})$ e·cm (2.1), $\bar{\theta}^{(90\% \text{ C.L.})} < 3 \times 10^{-10}$ (2.2). Therefore, the maximum allowed contribution of the QCD- $\bar{\theta}$ parameter is constrained by the experimental upper limit on the neutron EDM, $d_n^{(90\% \text{ C.L.})} < 1.8 \times 10^{-26}$ e·cm [25], which implies the constraint in Eq. 2.2, making the maximum allowed value of $d_n^{(\text{SM-}\bar{\theta})}$ the same as well. Therefore, we do not need any physics BSM effects to generate a neutron EDM. Any neutron EDM measured above the SM-CKM value would just be attributable to the QCD- $\bar{\theta}$ parameter. However, QCD- $\bar{\theta}$ could be close to zero, in which case the neutron could have an EDM wholly generated by SM-CKM, or in addition to possible BSM sources.

In πNN diagrams (eg. $p^+(n^0) \rightarrow n^0(p^+)\pi^{+(-)}$), one can easily interchange the proton with the neutron (and vice versa). This indicates that the SM-CKM contribution to the proton EDM is similar to that of the neutron EDM. Similarly, we will limit the contribution of QCD- $\bar{\theta}$ to the proton EDM, with the value of SM- $\bar{\theta}$ EDM obtained from the neutron. If the proton EDM was solely responsible for the ^{199}Hg EDM, then the constraint extracted from the measurement of the ^{199}Hg EDM is $d_p^{(90\% \text{ C.L.})} < 1.7 \times 10^{-25}$ e·cm [26].

$\Lambda^0, \Sigma^0, \Xi^0, \Lambda_c^+, \Xi_c^+$: The rest masses of the strange and charmed baryons, which we have considered, are within a factor of 2–3 of each other, unlike the orders of magnitude variation of masses in charged leptons, so we neglect any mass effects here. Ref. [29] estimates that $d_{\Lambda^0}^{(\text{SM-CKM})} \sim d_n^{(\text{SM-CKM})}/2$, and Ref. [30] shows the ratio between EDMs of Λ^0, Σ^0 , and Ξ^0 baryons; $\{d_{\Lambda^0}^{(\text{SM-CKM})} : d_{\Sigma^0}^{(\text{SM-CKM})} : d_{\Xi^0}^{(\text{SM-CKM})}\} = \{3 : -1 : 4\}$. Baryon EDM generating πNN diagrams involve conversion of $\{u, s, b\} \leftrightarrow \{d, c, t\}$. The SM-CKM EDM for neutrons and protons are comparable, since their quark content involves exchanging a u quark with a d quark. Similarly, we obtain $\{\Lambda_c^+, \Xi_c^+\}$ baryons by exchanging the s quark of $\{\Lambda^0, \Xi^0\}$ with a c quark, respectively. Consequently, we estimated the SM-CKM EDMs of the two charmed baryons as $d_{\Lambda^0}^{(\text{SM-CKM})} \sim d_{\Lambda_c^+}^{(\text{SM-CKM})}$ and $d_{\Xi^0}^{(\text{SM-CKM})} \sim d_{\Xi_c^+}^{(\text{SM-CKM})}$. Refs. [31, 32], give the EDM arising from QCD- $\bar{\theta}$ parameter for these baryons. But, coupled with the constraint upon $\bar{\theta}$ from the neutron EDM, the constraint on the SM- $\bar{\theta}$ EDM portion for these baryons is weaker than that for the neutron. Therefore, we will constrain the SM- $\bar{\theta}$ EDM for these baryons with the same constraint we used for the neutron or proton. For the strange and charmed baryons, the EDM of only one has been measured: $d_{\Lambda^0}^{(90\% \text{ C.L.})} < 1.2 \times 10^{-15}$ e·cm [33] using data from p^+X collisions in a fixed target experiment.

3. EDM of Atoms

Atoms may acquire a permanent EDM owing to the EDM of the nucleus, electrons, or from the CP-violating interactions between the electrons and the nucleus (or other electrons). Ideally, the electron cloud shields any nuclear EDM effectively suppressing the

contribution of the nuclear EDM to the atomic EDM [34]. Schiff shielding is not perfect in cases where [35]: (i) the electrons are relativistic [36], especially in high- Z paramagnetic atoms with a single unpaired electron like in the alkali atoms ^{85}Rb , ^{133}Cs and ^{210}Fr , but also in ^{205}Tl , and/or (ii) the nucleus has quadrupole and octupole deformations, like in diamagnetic atoms of ^{225}Ra and ^{223}Rn , and possibly also in ^{199}Hg and ^{129}Xe , and/or (iii) there exists dominant CP-violating interactions between constituents of the atoms. The semi-leptonic scalar [14] and tensor [26] e^- -N interaction parameters have already been constrained, respectively: $C_S^{(90\% \text{ C.L.})} < 7.2 \times 10^{-10}$ (3.1), $C_T^{(90\% \text{ C.L.})} < 1.3 \times 10^{-10}$ (3.2), where the paramagnetic atoms (and polar molecules) are sensitive to the C_S parameter and the diamagnetic atoms (and molecules) are sensitive to the C_T parameter.

^{85}Rb , ^{133}Cs , ^{210}Fr , ^{205}Tl : An enhanced electron EDM along with the semi-leptonic scalar interactions are responsible for the atomic EDM in paramagnetic atoms: $d_{\text{Atom}} \sim (\partial d_{\text{Atom}}/\partial d_e)d_e + (\partial d_{\text{Atom}}/\partial C_S)C_S$. For SM-CKM-EDM, the e^- -SM-CKM-EDM and the constraint upon C_S , in Eq. 3.1, have been scaled up by their respective factors in Table 1, and added together. For paramagnetic atoms, additional contribution to C_S enters through the $\bar{\theta}$ [57], and after combining with the constraint upon $\bar{\theta}$ in Eq. 2.2 yields: $C_S(\bar{\theta}) \sim 0.03\bar{\theta} \implies C_S(\bar{\theta}) < 9 \times 10^{-12}$ (3.3). The SM- $\bar{\theta}$ -EDM values were obtained by scaling up the SM- $\bar{\theta}$ -EDM of the electron and constraint on $C_S(\bar{\theta})$ above with their respective scaling factors in Table 1, and added together.

^{199}Hg : This nucleus may possess an intrinsic CP-violating nuclear Schiff moment which leads to a nuclear EDM [34]. A non-zero nuclear Schiff moment can give rise to an amplified EDM in an atom depending on the electron configuration and its CP-violating interactions with the nuclear Schiff moment [40]. ^{199}Hg and ^{129}Xe are particularly interesting diamagnetic atoms whose atomic EDM is thought to have contributions from the EDMs of the nucleons, electrons, and most importantly from a non-zero nuclear Schiff moment. The atomic EDM of ^{199}Hg [9] and its nuclear Schiff moment [41] can be decomposed to contributions from neutrons, protons, and electrons as: $d_{199\text{Hg}} = \rho_p \cdot d_p + \rho_n \cdot d_n + \kappa_S \cdot S + \mathcal{O}(d_e)$ (3.4), $S_{199\text{Hg}} = (0.20 \text{ fm}^2) d_p + (1.895 \text{ fm}^2) d_n$ (3.5), where $\kappa_S = -2.4 \times 10^{-4} \text{ fm}^2$ [26], $\rho_p = (-0.56 \times 10^{-4})$ [9], and $\rho_n = (-5.3 \times 10^{-4})$ [9]. Given that the electron SM-CKM-EDM and its allowed SM- $\bar{\theta}$ -EDM are about 12 orders of magnitude lower than that of proton or neutron, we can safely neglect the contribution of the d_e to the atomic EDM of ^{199}Hg . Using the SM-CKM-EDM and SM- $\bar{\theta}$ -EDM values for the neutron and proton, we can write the theoretical expectations for the nuclear Schiff moment of ^{199}Hg as: $|S_{199\text{Hg}}^{\text{(SM-CKM)}}| \sim 4.2 \times 10^{-19} \text{ e}\cdot\text{fm}^3$ and $|S_{199\text{Hg}}^{\text{(SM-}\bar{\theta}\text{)}}| < 6.3 \times 10^{-13} \text{ e}\cdot\text{fm}^3$. Along with the Schiff moment values calculated here, and the values of SM-CKM EDM and SM- $\bar{\theta}$ EDM associated with d_p and d_n , we arrived at $\{|d_{199\text{Hg}}^{\mathcal{T}(\text{SM-CKM})}|, |d_{199\text{Hg}}^{\mathcal{T}(\text{SM-}\bar{\theta}\text{)}}|\} = \{2.2 \times 10^{-35}, 6.2 \times 10^{-30}\} \text{ e}\cdot\text{cm}$.

The dependence of SM-CKM-EDM of ^{199}Hg on C_T is: $\partial d_{199\text{Hg}}/\partial C_T = 3 \times 10^{-20}$ [10], and combining this with the constraint in Eq. 3.2 essentially yields the experimental limit. Similarly, the dependence on C_S : $\partial d_{199\text{Hg}}/\partial C_S = -5.9 \times 10^{-22}$ [10], combined with the constraint in Eq. 3.1 gives $4.3 \times 10^{-31} \text{ e}\cdot\text{cm}$, while combining the above dependence *w.r.t.* C_S

Atom	$ \partial d_{\text{Atom}}/\partial d_e $	$ \partial d_{\text{Atom}}/\partial C_S $
^{89}Rb	25.7 [37]	1.2 [37]
^{210}Fr	903 [38]	5.0 [10]
^{133}Cs	123 [37]	7.1 [11]
^{205}Tl	573 [39]	70 [11]

Table 1: Atomic EDM *w.r.t.* (i) the e^- EDM [9] and (ii) C_S ($\times 10^{-19} \text{ e}\cdot\text{cm}$).

with Eq. 3.3, yields 5.3×10^{-33} e · cm. On the other hand, $C_S(\bar{\theta})$ in Eq. 3.3 combined with the $\partial d_{199\text{Hg}}/\partial C_S$ coefficient gives 5.3×10^{-33} e · cm, so we shall neglect this and retain the SM- $\bar{\theta}$ previously obtained through the Schiff moment. In the case of ^{199}Hg , any statistically significant EDM can be explained within the SM-CKM through C_S or C_T parameters or SM- $\bar{\theta}$ framework through the QCD- $\bar{\theta}$.

^{129}Xe : Scaling the values of $\{|d_{199\text{Hg}}^{\mathcal{T}(\text{SM-CKM})}|, |d_{199\text{Hg}}^{\mathcal{T}(\text{SM-}\bar{\theta})}|\}$ by the \mathcal{T} -factor indicated in Table 2 yields, $\{|d_{129\text{Xe}}^{\mathcal{T}(\text{SM-CKM})}|, |d_{129\text{Xe}}^{\mathcal{T}(\text{SM-}\bar{\theta})}|\} = \{3.0 \times 10^{-36}, 8.4 \times 10^{-31}\}$ e · cm. By combining the limits in Eqs. 3.1 and 3.2, with $\partial d_{129\text{Xe}}/\partial C_S = -4.4 \times 10^{-23}$ [10] and $\partial d_{129\text{Xe}}/\partial C_T$ from Table 2, yields 3.2×10^{-32} e · cm and

7.8×10^{-31} e · cm, respectively. Like in the case of ^{199}Hg we will retain the value of $d_{129\text{Xe}}^{\mathcal{T}(\text{SM-}\bar{\theta})}$. **^{225}Ra , ^{223}Rn :** Higher electric and magnetic moments are not fully shielded by the Schiff screening. In such cases, not only is the nuclear Schiff moment contribution enhanced by the electron cloud, but there are additional enhancement factors contributing to the nuclear Schiff moment itself due to the octupole and quadrupole deformations of the nucleus [42, 50]. Scaling up $\{|d_{199\text{Hg}}^{\mathcal{T}(\text{SM-CKM})}|, |d_{199\text{Hg}}^{\mathcal{T}(\text{SM-}\bar{\theta})}|\}$ using the factors in Table 2 gives the contributions from Schiff moment: $\{|d_{225\text{Ra}(^{223}\text{Rn})}^{\mathcal{T}(\text{SM-CKM})}|, |d_{225\text{Ra}(^{223}\text{Rn})}^{\mathcal{T}(\text{SM-}\bar{\theta})}|\} = \{1.6(0.63) \times 10^{-32}, 4.5(1.8) \times 10^{-27}\}$ e · cm. Combining the $\partial d_{\text{Atom}}/\partial C_T$ coefficients in Table 2 with the constraint in Eq. 3.2 gives, $\{|d_{225\text{Ra}(^{223}\text{Rn})}^{\mathcal{T}(\text{SM-CKM})}|\} = 6.9(0.65) \times 10^{-30}$ e · cm.

4. EDM of Molecules

All the experiments discussed so far, searching for EDMs in sub-atomic particles and atoms, applied an electric field, E , on the order of \sim kV/cm, to induce (Stark)

energy level splitting owing to a possible non-zero EDM. Polar molecules contain charged atoms, which have large intra-molecular electric fields, $E_{\text{Mol.}}$, on the order of GV/cm. The EDM sensitivity achievable is directly proportional to the electric field we can apply. Experiments searching for EDMs in molecules use this intra-molecular electric field as a key to achieve higher EDM sensitivities, compared to atomic EDM experiments.

PbO, ThO, HfF⁺, YbF: In a polar molecule, the valence electrons of the atom feel the large intra-molecular electric field. Each of these polar molecules have a particular associated molecular electric field and the experiments measuring their EDM used an additional applied electric field, so their sensitivity to the electron EDM varies. In order to compare these molecular EDMs, we normalized the molecular EDM measured with the ratio of molecular electric field to the applied electric field, listed in Table 3. The corresponding SM-CKM-EDMs and SM- $\bar{\theta}$ -EDMs are obtained using: $d_{\text{Mol.}}^{\{\text{SM-CKM}\}, \{\text{SM-}\bar{\theta}\}} \sim [d_e^{\{\text{SM-CKM}\}, \{\text{SM-}\bar{\theta}\}} + (\partial d_{\text{Mol.}}/\partial C_S)\{C_S^{(90\% \text{ C.L.})}, C_S(\bar{\theta})\}] \times (E_{\text{Mol.}}/E)$.

^{225}RaF : The relevant molecular electric field felt by the radium nuclei in the ^{225}RaF molecule is $E_{225\text{RaF}} = 130$ MV/cm [62]. The radium EDM experiment plans to apply an electric field of $E = 300$ kV/cm [63] using niobium electrodes. The SM-CKM and SM-

Atom	$\kappa_S^{(\text{Atom})}/\kappa_S^{199\text{Hg}}$	$d_{(\text{Atom})}^{\mathcal{T}}/d_{199\text{Hg}}^{\mathcal{T}}$	$ \partial d_{\text{Atom}}/\partial C_T $
^{129}Xe	0.14 [42]	1	0.6 [11]
^{225}Ra	3[42]	240 [43]	5.3 [11]
^{223}Rn	1.2 [42]	240 [44]	0.5 [10]

Table 2: Factors *w.r.t.* that in ^{199}Hg (i) nuclear Schiff moment to the atomic EDM, and (ii) nuclear quadrupole & octupole deformation to the nuclear Schiff moment. Dependence of atomic EDM on (iii) C_T ($\times 10^{-20}$ e · cm).

Mol.	$E_{\text{Mol.}}$ (GV/cm)	E (V/cm)	$ \partial d_{\text{Mol.}}/\partial C_S $
HfF ⁺	23 [51]	24 [52, 53]	8.9 [11]
PbO	25 [54, 55]	{100, 125} [56]	~ 4.2 [57]
YbF	14.5 [58]	10k [59]	8.6 [11]
ThO	78 [60, 61]	{80, 140} [14]	13 [11]

Table 3: $E_{\text{Mol.}}$, E , EDM factor *w.r.t.* C_S (10^{-21} e · cm).

$\bar{\theta}$ contributions to the EDM of ^{225}RaF were obtained by scaling up SM-CKM-EDM and SM- $\bar{\theta}$ -EDM values associated with atomic ^{225}Ra with the ratio of $(E_{\text{Mol.}}/E)$.

TIF: TIF molecule is a diamagnetic system, similar to the ^{199}Hg atom. The EDM of TIF is $d_{\text{TIF}} \sim 81d_e + d_p/2 + 2.9 \times 10^{-18}C_S + 2.7 \times 10^{-16}C_T$ [64, 11]. Clearly one could neglect the contribution of electron or proton EDMs. The SM-CKM-EDM for TIF dominantly originating from C_T is $|d_{\text{TIF}}^{\text{SM-CKM}}| = 3.5 \times 10^{-26}$ e-cm. SM- $\bar{\theta}$ contributions to the EDM of TIF arising from the proton is 9×10^{-27} e-cm, while the same originating from QCD- $\bar{\theta}$ and via the scalar semi-leptonic interaction can be neglected.

5. Conclusion

Recent studies [65, 66] have also shown that the e^- -SM-CKM-EDM could be much higher, using hadronic loops instead of quark 4-loops used in Ref. [12], which may dramatically improve the estimates which depend on the e-EDM. These estimates of SM-CKM and SM- $\bar{\theta}$ EDMs for sub-atomic particles, have also been used in Refs. [17, 67, 68]. A statistically significant measurement in any one species would not help us understand the origins of its EDM. In Figure 1, for sub-atomic particles, the white space between the SM- $\bar{\theta}$ EDM portion of the SM theoretical estimate and the experimental constraint could be fertile ground in which to search for physics beyond the SM (BSM). Given that the white space between the charged leptons is the largest (over ~ 8 orders of magnitude), they may be the apt systems in which to search for BSM effects given their low SM background. Additionally, new and improved efforts to measure the EDM of p^+ , TIF, Ra, and RaF may make their status comparable to the current status of n^0 , ^{199}Hg , and ThO.

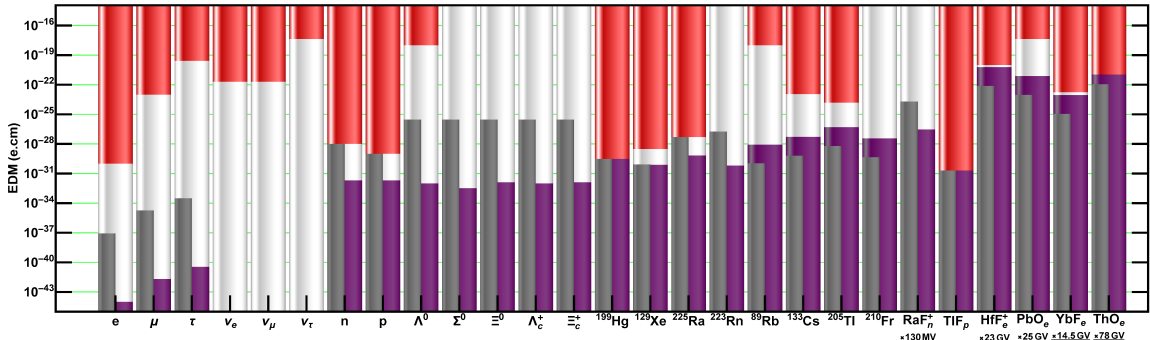


Figure 1: Panel showing the measured upper limit at 90% C.L. (red) and the reach of SM theoretical values of the EDM from the SM-CKM (purple) and SM- $\bar{\theta}$ (gray) mechanisms.

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