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Uncovering axion and BSM CP violations with EDMs

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Electric dipole moments (EDMs) of nuclear or atomic elements may originate either from the QCD θ-term in the Standard Model or from new CP violation beyond the Standard Model (BSM). If the strong CP problem arising from the smallness of the QCD θ-parameter is explained by an axion, the θ-parameter is determined by the axion vacuum value. Yet it can have a nonzero value close to the current experimental bound due to either BSM CP violation at low energy scales or high scale breaking of the Peccei-Quinn (PQ) symmetry caused for instance by quantum gravity effect. We examine to what extent EDMs can discriminate between these two origins of nonzero axion vacuum value. Our results imply that EDMs can provide information not only on BSM CP violation, but also on the origin of the axion vacuum value, therefore on the UV quality of the PQ symmetry in the axion solution of the strong CP problem.

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1. Introduction and conclusion

Permanent electric dipole moment (EDM) of particles provides a sensitive tool to probe CP violation (CPV) in the fundamental laws of nature. The Standard Model (SM) of particle physics involve the two CP violating parameters, the Kobayashi-Maskawa phase $\delta_{\rm KM}$ and the QCD angle $\bar{\theta}$, which are given by

$$\delta_{\rm KM} = \arg \cdot \det([Y_u Y_u^\dagger, Y_d Y_d^\dagger]), \quad \bar{\theta} = \theta_0 + \arg \cdot \det(Y_u Y_d), \tag{1}$$

where Y_u and Y_d are the Yukawa couplings of the 3 generations of the up and down type quarks, and θ_0 is the bare QCD angle. The observed CPV in the weak interactions implies $\delta_{\rm KM} = \mathcal{O}(1)$, while the non-observation of CPV in the strong interactions leads to the upper bound $|\bar{\theta}| \lesssim 10^{-10}$.

Although $\delta_{\rm KM}$ is of order unity, EDMs induced by $\delta_{\rm KM}$ are highly suppressed by the small quark masses and mixing parameters, and therefore have a value well below the current experimental bounds. On the other hand, $\bar{\theta}$ can generate hadronic EDMs near the current bound if $\bar{\theta}$ has a value near 10^{-10}. Generically there can also be new CPV beyond the SM (BSM), which may give EDMs near the current experimental bounds. Therefore, once a nonzero hadronic EDM were detected experimentally, a key question is whether it originates from $\bar{\theta}$ or from BSM CPV. To answer this question, one needs to measure multiple EDMs in the experimental side, and examine in the theory side if the observed pattern of EDMs can be explained by $\bar{\theta}$, or they require BSM CPV [1–3].

On the other hand, the smallness of $\bar{\theta}$ causes a severe fine-tuning problem, the strong CP problem (see for instance [4] for a review). An appealing solution to this problem is to introduce a global $U(1)$ Peccei-Quinn (PQ) symmetry [5] which is non-linearly realized in low energy limits, under which the associated Nambu-Goldstone boson, the axion $a(x)$, transforms as

$$U(1)_{\rm PQ}: \quad a(x) \to a(x) + \text{constant}. \tag{2}$$

A key assumption in this solution is that $U(1)_{\rm PQ}$ is broken *dominantly* by the QCD anomaly, i.e. by the following axion coupling to the gluons in low energy effective theory:

$$\frac{g_s^2}{32\pi^2}\frac{a(x)}{f_a} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}, \tag{3}$$

generating an axion potential having the minimum at $\langle a(x)\rangle = 0$, yielding $\bar{\theta} \equiv \langle a \rangle / f_a = 0$.

However, this is not the end of the story. Generically there can be additional physics shifting the axion vacuum value, which would give $\bar{\theta} \neq 0$. The two most prominent examples are

(i) BSM CP-violating low energy effective interactions of the gluons and light quarks,

(ii) UV-originated $U(1)_{\rm PQ}$-breaking such as quantum gravity effects, (4)

which would yield

$$\bar{\theta} = \langle a(x)\rangle / f_a = \bar{\theta}_{\rm BSM} + \bar{\theta}_{\rm UV}, \tag{5}$$

where $\bar{\theta}_{\rm BSM}$ and $\bar{\theta}_{\rm UV}$ denote the axion vacuum value induced by (i) and (ii), respectively. As (i) and (ii) affect EDMs in different way, EDMs may provide a way to discriminate between these two origins of the axion vacuum value. In this talk, we discuss such a possibility for the case that BSM CPV is mediated to the SM sector dominantly by the gluons or the Higgs boson, in which its low energy consequence is well approximated by the chromo-EDM (CEDM) of the gluons and quarks [6].

Specifically we consider two simple scenarios for BSM CPV at the scale Λ which is presumed to be not far away from the weak scale:

$$\text{(1) Quark CEDM domination} \quad \text{(2) Gluon CEDM domination,} \tag{6}$$

and examine the EDM portfolio in the following three distinctive limits of the UV-originated PQ breaking:

$$\begin{aligned} &(a)\ \ \bar{\theta}_{\rm UV} \text{ is small enough to be ignored,} \\ &(b)\ \ \bar{\theta}_{\rm UV} \text{ is the dominant source of EDMs,} \\ &(c)\ \ \bar{\theta}_{\rm UV} \text{ is nearly cancelled by } \bar{\theta}_{\rm BSM}. \end{aligned} \tag{7}$$

We then find that the EDMs of some nuclear and atomic elements can discriminate among the following four different scenarios:

$$\text{(I)}\ \ (1\text{-}a)\,,\quad \text{(II)}\ \ (1\text{-}c)\,,\quad \text{(III)}\ \ (2\text{-}a) \text{ or } (2\text{-}c)\,,\quad \text{(IV)}\ \ (1\text{-}b) \text{ or } (2\text{-}b). \tag{8}$$

The scenario (II) is possible only when $\bar{\theta}_{\rm UV}$ is nearly cancelled by $\bar{\theta}_{\rm BSM}$, and therefore it might be considered to be less plausible compared to other scenarios. Note that (IV) corresponds to the limit when BSM CPV is negligible compared to $\bar{\theta}_{\rm UV}$, while (III) is the case of gluon CEDM domination. Our results indicate that EDMs indeed can provide information not only on BSM CPV, but also on the origin of the axion vacuum value, therefore on the UV quality of the PQ symmetry.

2. Axion vacuum value with BSM CP violation and high scale PQ breaking

In models with a QCD axion solving the strong CP problem, the axion potential is given by

$$V(a) = V_{\rm QCD}(a) + \delta V(a) \tag{9}$$

where

$$V_{\rm QCD}(a) \simeq -\frac{f_\pi^2 m_\pi^2}{(m_u + m_d)}\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos(a/f_a)} \tag{10}$$

is the potential induced by the axion coupling (3), and δV denotes the additional potential which generically can have a minimum at $\langle a \rangle \neq 0$. (Here $m_{u,d}$ are the light quark masses.) There can be two different potentially dominant sources of δV. The first is the combined effect of the the axion coupling (3) and a CP violating effective interaction of the gluons and/or light quarks around the QCD scale. It includes first of all the SM contribution $\delta V_{\rm SM} \sim 10^{-19} f_\pi^2 m_\pi^2 \sin\delta_{\rm KM} \sin(a/f_a)$ [7], yielding

$$\bar{\theta}_{\rm SM} = \frac{\langle a \rangle_{\rm SM}}{f_a} \sim 10^{-19} \sin\delta_{\rm KM}, \tag{11}$$

which is too small to be phenomenologically interesting in the near future. On the other hand, in the presence of BSM physics, the resulting $\bar{\theta}$ might be as large as 10^{-10}. For instance, if those BSM physics generates CP-odd effective interactions of the gluons and/or light quarks around the QCD scale, which are given by

$$\mathcal{L}_{\rm eff} = \sum_i \lambda_i O_i(x), \tag{12}$$

where $O_i(x)$ are the CP-odd local composite operators of the gluons and light quarks, and λ_i are the associated Wilson coefficients, an additional axion potential is generated as

$$f_a \frac{\partial \delta V_{\rm BSM}}{\partial a}\bigg|_{a=0} \sim \sum_i \lambda_i \int d^4x \left\langle \frac{g_s^2}{32\pi^2} G\tilde{G}(x) O_i(0) \right\rangle_{a=0}. \tag{13}$$

Obviously this results in a nonzero axion vacuum value

$$\bar{\theta}_{\rm BSM} = \frac{\langle a \rangle_{\rm BSM}}{f_a} \sim \frac{\sum_i \lambda_i \int d^4x \left\langle \frac{g_s^2}{32\pi^2} G\tilde{G}(x) O_i(0) \right\rangle_{a=0}}{f_\pi^2 m_\pi^2} \tag{14}$$

which can be near 10^{-10} for appropriate values of λ_i.

The second source of δV is UV-originated PQ breaking such as quantum gravity effects. Studies of axions in string theory and also of axionic Euclidean wormholes imply that string/brane instantons or gravitational wormholes generate an additional axion potential [8–10]

$$\delta V_{\rm UV} = \Lambda_{\rm UV}^4 e^{-S_{\rm ins}} \cos(a/f_a + \delta_{\rm UV}), \tag{15}$$

where $\Lambda_{\rm UV}$ is a model-dependent UV scale, $S_{\rm ins}$ is the Euclidean action of the associated string/brane instanton or of the Euclidean wormhole, and $\delta_{\rm UV}$ is a phase angle which is generically of order unity. This additional axion potential shifts the axion vacuum value as

$$\bar{\theta}_{\rm UV} = \frac{\langle a \rangle_{\rm UV}}{f_a} \sim e^{-S_{\rm ins}} \Lambda_{\rm UV}^4 \sin \delta_{\rm UV} / f_\pi^2 m_\pi^2 \tag{16}$$

which again can have a value near 10^{-10}.

As was noted in the previous section, the above two origins of nonzero axion vacuum value may give distinguishable patterns of EDMs, which will be discussed in the next section.

3. Nucleon and some nuclear/atomic EDMs

To be specific, we focus on BSM CPV which is mediated to the SM sector dominantly by the gluons or the Higgs boson in such a way that its consequence at the BSM scale Λ is well approximated by the CEDMs of the gluons and quarks. Including the quark EDMs generated by the renormalization group (RG) evolution at lower energy scales, the CP-violating effective lagrangian at $\mu < \Lambda$ is given by

$$\mathcal{L}_{\rm eff}(\mu) = \frac{1}{3} w f^{abc} G^{a\mu}_{\alpha} G^{b\delta}_{\mu} \widetilde{G}^{c\alpha}_{\delta} - \frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma^{\mu\nu} G_{\mu\nu} \gamma_5 q - \frac{i}{2} \sum_q d_q e \bar{q} \sigma^{\mu\nu} F_{\mu\nu} \gamma_5 q. \tag{17}$$

The Wilson coefficients in $\mathcal{L}_{\rm eff}$ obey the RG equation

$$\frac{d\mathbf{C}}{d\ln\mu} = \frac{g_s^2}{16\pi^2}\gamma\,\mathbf{C}, \tag{18}$$

where

$$\mathbf{C} \equiv \begin{pmatrix} C_1 = d_q/m_q Q_q \\ C_2 = \tilde{d}_q/m_q \\ C_3 = w/g_s \end{pmatrix}, \quad \gamma = \begin{pmatrix} 32/3 & 32/3 & 0 \\ 0 & 28/3 & -6 \\ 0 & 0 & 3+2n_f+\beta_0 \end{pmatrix}$$

for n_f denoting the number of active light Dirac quarks at the scale μ, and $\beta_0 \equiv (33-2n_f)/3$. Here we assume $\tilde{d}_q = C_2 m_q$ for a flavor-independent coefficient C_2, and also the quark EDMs at Λ are negligible, so $d_q(\mu=\Lambda)=0$. An important consequence of the above RG evolution is the low energy CEDM of light quarks induced by the gluon CEDM, which is given by

$$\frac{\Delta\tilde{d}_q}{m_q}(1\ \text{GeV}) \simeq \begin{cases} 0.41\,w(1\ \text{GeV}), & \Lambda = 1\ \text{TeV} \\ 0.53\,w(1\ \text{GeV}), & \Lambda = 10\ \text{TeV}. \end{cases} \tag{19}$$

It turns out that this RG induced CEDM of light quarks play an important role for discriminating the gluon CEDM domination scenario (III) from the $\bar{\theta}$-domination scenario (IV) [6].

For given values the quark and gluon CEDMs at Λ, one can derive the resulting CEDMs and EDMs at $\mu = 1$ GeV. One can also use the results of [11–13] to find the following nucleon EDMs which are induced by $\bar{\theta}$, the gluon and light quark CEDMs, and the light quark EDMs renormalized at $\mu = 1$ GeV:

$$\begin{aligned} d_p(\bar{\theta},\tilde{d}_q,d_q,w) =& -0.46\times10^{-16}\bar{\theta}\,e\,\text{cm} + e\left(-0.17\tilde{d}_u + 0.12\tilde{d}_d + 0.0098\tilde{d}_s\right) \\ &+ 0.36 d_u - 0.09 d_d - 18w\,e\,\text{MeV}, \\ d_n(\bar{\theta},\tilde{d}_q,d_q,w) =& 0.31\times10^{-16}\bar{\theta}\,e\,\text{cm} + e\left(-0.13\tilde{d}_u + 0.16\tilde{d}_d - 0.0066\tilde{d}_s\right) \\ &- 0.09 d_u + 0.36 d_d + 20w\,e\,\text{MeV}. \end{aligned} \tag{20}$$

If the strong CP problem is solved by a QCD axion, $\bar{\theta}$ is determined by the axion vacuum value as discussed in Section 2:

$$\bar{\theta} \equiv \langle a\rangle/f_a = \bar{\theta}_{\rm UV} + \bar{\theta}_{\rm BSM}. \tag{21}$$

Using the result of [11] together with the naive dimensional analysis, one finds

$$\bar{\theta}_{\rm BSM} = \frac{0.8\text{GeV}^2}{2}\sum_{q=u,d,s}\frac{\tilde{d}_q}{m_q} + O(4\pi f_\pi^2 w). \tag{22}$$

Combining this with (20), we finally find

$$\begin{aligned} d_p^{\rm PQ}(\bar{\theta}_{\rm UV},\tilde{d}_q,d_q,w) =& -0.46\times10^{-16}\bar{\theta}_{\rm UV}\,e\,\text{cm} - e\left(0.58\tilde{d}_u + 0.073\tilde{d}_d\right) \\ &+ 0.36 d_u - 0.089 d_d - 18w\,e\,\text{MeV}, \\ d_n^{\rm PQ}(\bar{\theta}_{\rm UV},\tilde{d}_q,d_q,w) =& 0.31\times10^{-16}\bar{\theta}_{\rm UV}\,e\,\text{cm} + e\left(0.15\tilde{d}_u + 0.29\tilde{d}_d\right) \\ &- 0.089 d_u + 0.36 d_d + 20w\,e\,\text{MeV} \end{aligned} \tag{23}$$

for the nucleon EDMs when the strong CP problem is solved by a QCD axion. In Fig. 1, we use the above result to depict the nucleon EDMs for the 4 scenarios defined in (8). Our results show that the nucleon EDMs clearly discriminate the scenario (II), i.e. the quark CEDM domination with $\bar{\theta}_{\rm BSM}$ nearly cancelled by $\bar{\theta}_{\rm UV}$, from the other three scenarios which include the gluon CEDM domination scenario (II) and the $\bar{\theta}$-domination scenario (IV).

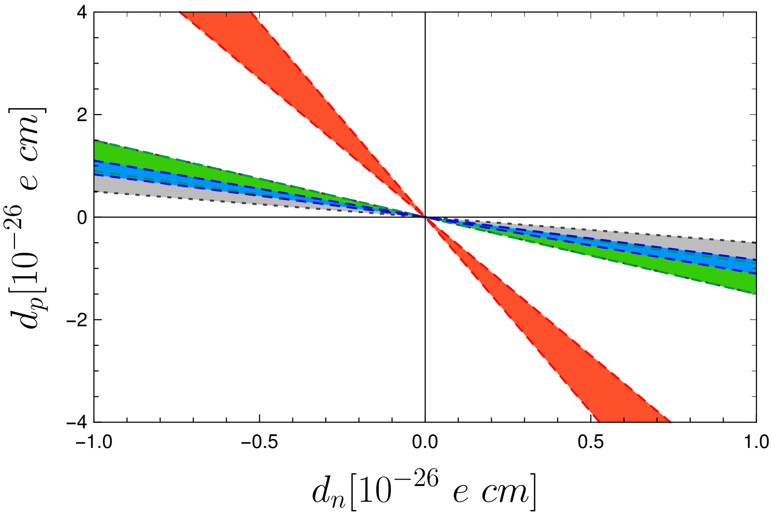

Figure 1: Nucleon EDMs in the scenarios (I) (blue), (II) (red), (III) (green), (IV) (gray). Here CEDMs are assumed to be generated at $\Lambda = 1$ TeV, however our results are not sensitive to the value of Λ.

To get further information, one may consider some nuclei or atomic EDMs which are sensitive to CP-violating pion-nucleon couplings. Those examples include D (deuteron) and $^3\mathrm{He}^{++}$ (helion) whose EDMs can be measured by the storage ring method [14], and also diamagnetic atoms like $^{225}\mathrm{Ra}$ and $^{129}\mathrm{Xe}$. Recent calculations show that [3, 14, 15]

$$\begin{aligned}
d_D &= 0.94(1)(d_n + d_p) + 0.18(2)\bar{g}_1\, e\,\mathrm{fm}, \\
d_{\rm He} &= 0.9 d_n - 0.05 d_p + [0.10(3)\bar{g}_0 + 0.14(3)\bar{g}_1]\ e\,\mathrm{fm}, \\
d_{\rm Ra} &= 7.7\times 10^{-4}\ [(2.5\pm 7.5)\bar{g}_0 - (65\pm 40)\bar{g}_1]\ e\,\mathrm{fm}, \\
d_{\rm Xe} &= 1.3\times 10^{-5} d_n - 10^{-5}\ [1.6\bar{g}_0 + 1.7\bar{g}_1]\ e\,\mathrm{fm},
\end{aligned} \tag{24}$$

where the CP-odd pion-nucleon couplings $\bar{g}_0$ and $\bar{g}_1$ are defined as

$$\bar{g}_0 \bar{N}\frac{\vec{\sigma}}{2}\cdot\vec{\pi}N + \bar{g}_1 \pi_3 \bar{N}N. \tag{25}$$

The pion-nucleon couplings induced by $\bar{\theta}$ and the gluon and light quark CEDMs were discussed in [3, 14, 15], yielding

$$\begin{aligned}
&\bar{g}_0(\bar{\theta}) = (15.7\pm 1.7)\times 10^{-3}\bar{\theta}, \quad \bar{g}_1(\bar{\theta}) = -(3.4\pm 2.4)\times 10^{-3}\bar{\theta}, \\
&\bar{g}_0(\tilde{d}_q) \simeq -0.002(3) C_2\,\mathrm{GeV}^2, \quad \bar{g}_1(\tilde{d}_q) \simeq -0.096(15)\, C_2\,\mathrm{GeV}^2, \\
&\bar{g}_0(w) = (m_u + m_d) O(4\pi f_\pi w), \quad \bar{g}_1(w) \simeq \pm(2.6\pm 1.5)\times 10^{-3} w\,\mathrm{GeV}^2,
\end{aligned} \tag{26}$$

for $\bar{\theta}$, w and $C_2 = \tilde{d}_q/m_q$ renormalized at $\mu = 1$ GeV.

One can now combine (22) with (24) and (26) to get the corresponding nuclear and atomic EDMs in the presence of a QCD axion. In Fig. 2, we depict the results for the four scenarios (I)-(IV) that we are concerned with. We can see tha the quark CEDM dominantion scenarios, i.e. (I) and (II), show clearly different patterns from the gluon CEDM or $\bar{\theta}$ domination scenarios, i.e. (III) and (IV). We also find that the EDMs of $^3He^{++}$ and ^{129}Xe are able to distinguish between the gluon CEDM domination scenario (III) and the $\bar{\theta}$ domination scenario (IV), which is essentially due to their sensitivity on the coupling $\bar{g}_0$. Combining the nucleon EDMs with these nuclear and atomic EDMs, we see that future measurements of those EDMs will be able to provide information not only on BSM CP violation, but also on the origin of the axion VEV, therefore on the UV quality of the PQ symmetry in the axion solution of the strong CP problem.

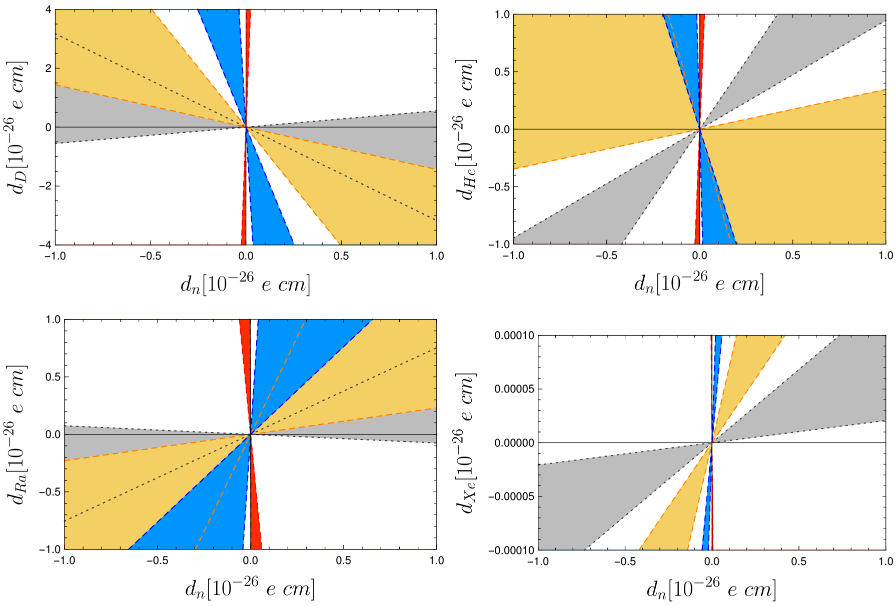

Figure 2: Nuclei and atomic EDMs in the scenarios (I) (blue), (II) (red), (III) (orange), (IV) (gray). Again we assume $\Lambda = 1$ TeV, but the results are not sensitive to the value of Λ.

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