Theoretical perspective on EDMs and the strong CP problem

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Electric Dipole Moments as Sensitive Probes of Flavor Physics

Two aspects:

1. Generic new physics: leads to large violations of CP. Potentially important for understanding the baryon asymmetry of the universe.
2. Generic new physics, unless the scale is extremely high, leads to large electric dipole moments for the neutron, electron. (An observation which has long created unease about the expectations for new physics at the TeV scale).
3. The θ parameter remains a great puzzle. Tempting to sweep under the rug. If for some reason small at high scales, Standard Model corrections *extremely* small. But generic new physics, even at extremely high energy scales, generates large contributions, In particular, theories of flavor, at arbitrary scales, like to produce large contributions.

Outline

1. Dimension 5/6 operators and Generic Flavor Physics at scale M
2. The Strong CP Problem: Lightning review and assessment with the SM
3. Solutions of the Strong CP Problem: An Assessment
4. Axion Cosmology and Axion Searches: Old and New Ideas

Strong CP vs “Ordinary" CP violation and Electric Dipole Moments

Loosely speaking:

1. Dimension five (six) operators: neutron, lepton edm’s.
2. Dimension Four operators: neutron edm.

θ sensitive to physics at all scales. But if interesting flavor physics, even at rather high scales, electric dipole operators may detect: a big lever arm in energy scales.

Dipole Moments from Dimension $5/6$ Operators

$$\mathcal{L}_{d_q} = \frac{a}{M^2} Q\,\sigma_{\mu\nu} \begin{pmatrix} \phi \bar{u} \\ \phi^* \bar{d} \end{pmatrix} \tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{d_e} = \frac{a}{M^2}\, L \sigma_{\mu\nu} \phi^* \bar{e}\, \tilde{F}^{\mu\nu}.$$

Here M is some scale of new physics; a is a pure number, which may depend on couplings, mixing angles, loop factors and the like.

If $a \sim 0.01$, severe limits.

d_n: $M > 10^6\ \mathrm{GeV}$

d_e: $M > 10^6\ \mathrm{GeV}$.

Supersymmetry and Dimension $5/6$ Operators

TeV scale supersymmetry is under severe stress. But edm's were among the reasons to suspect that supersymmetry, if present at all in nature, might be found at a significantly higher scale.

With generic soft breakings, many new sources of CP violation, and CP violation readily fed to low energy physics. EdM's at one loop, so $a \sim 10^{-2},~10^{-3}$. Corresponds to $M \sim 10^6~\mathrm{GeV}$.

With TeV supersymmetry, theorists devoted much effort to models which might suppress *a*. With some flavor symmetry, suppression.

1. Gauge Mediation
2. Minimal Flavor Violation
3. Actual Flavor Models (Leurer, Nir, Seiberg; Dine, Leigh)

Even with flavor symmetry, CP constraining.

Where we are in 2019

We are no longer convinced that hierarchy points to precisely TeV scale for new physics. Many ideas, for example, place supersymmetry at a higher scale (e.g. split susy); similarly for other new physics. Rather than looking for excuses to explain the smallness of EdM's, it is now clear that these should be viewed as potential probes for very high scale physics.

E.g: Split supersymmetry: susy scale 100 TeV or so. Flavor constraints weak; without flavor, d_n comparable to experimental limits.

Dimension Four Operators

Here we encounter θ. Can view as

$$\delta\mathcal{L} = \frac{\theta}{16\pi^2} F\tilde{F}; \quad \arg\det(y_U y_D). \tag{1}$$

By field redefinitions, one can be rotated one into another.

Because dimension four, sensitive to arbitrarily high scales of new physics.

d_n and the Strong CP Problem

d_n can be calculated reliably in terms of known quantites of hadronic physics:

$$d_n = 5.2 \times 10^{-16} \theta cm \tag{2}$$

$d_n < 3 \times 10^{-26}\ \mathrm{e\ cm} \Rightarrow \theta < 10^{-10}$.

This is a puzzle. Why such a small dimensionless number?

$\theta \to 0$: strong interactions preserve CP. If not for the fact that the rest of the SM violates CP, would be *natural*.

Loop corrections to θ in the Standard Model are highly suppressed. Focussing on divergent corrections, one requires Higgs loops. These involve the Hermitian matrices

$$A = y_d^\dagger y_d; \quad B = y_u^\dagger y_u \tag{3}$$

Contributions to θ are proportional to traces of the form

$$Tr(ABA^2B\dots) \tag{4}$$

The first complex combination involves six matrices, and an additional $U(1)$ gauge loop [Ellis, Gaillard].

Distinction from Other Naturalness Problems

Why might $\theta(\Lambda_{SM})$ be small?

1. Probably not anthropic
2. Because dimension four, doesn't point to other scales.

Among naturalness problems, the strong CP problem is special in that it is of almost no consequence. We don't have to invoke anthropic selection to realize that if the cosmological constant was a few orders of magnitude larger than observed, the universe would be dramatically different. The same is true for the value of the weak scale and of the light quark and lepton masses. But if θ were, say, 10^{-3}, nuclear physics would hardly be different than we observe, since effects of θ are shielded by small quark masses.

So whatever one thinks about the anthropic principle, it is unlikely to be relevant here. Strong CP requires some principled explanation. The question is: can we find it?

Possible Resolutions

1. $m_u = 0$ If true, $u \rightarrow e^{-i\frac{\theta}{2}\gamma_5} u$ eliminates θ from the lagrangian. An *effective* m_u might be generated from non-perturbative effects in the theory (Georgi, McArthur; Kaplan, Manohar) Could result as an accident of discrete flavor symmetries (Banks, Nir, Seiberg), or a result of “anomalous" discrete symmetries as in string theory (M.D.) But lattice gauge computations exclude.
2. CP exact microscopically, $\theta = 0$; spontaneous breaking gives the CKM phase but leads, under suitable conditions, to small effective θ (Nelson, Barr). In critical string theories, CP is an exact (gauge) symmetry, spontaneously broken at generic points in typical moduli spaces. A plausible framework. Might be tied to theories of flavor.
3. A new, light particle called the axion dynamically cancels off θ.

Solutions of the Strong CP Problem: An Assessment

1. $m_u = 0$. Lattice computations seem to rule out (the required non-perturbative effects do not seem to be large enough).
2. Spontaneous CP: special properties required to avoid large θ once CP is spontaneously broken. What would single out such theories?
3. Axions: Constraints on the axion scale (mass) from cosmology/astrophysics. Here the question is: why is the Peccei-Quinn symmetry so good?

Summary of lattice results for light quark masses

Current results from lattice simulations (summarized by the FLAG working group) are inconsistent with $m_u = 0$.

$$m_u = 2.16\ (9)(7)\mathrm{MeV} \quad m_d = 4.68\ (14)(7)\mathrm{MeV} \tag{5}$$

$$m_s = 93.5(2.5)\mathrm{MeV}$$

Numbers are in $\overline{MS}$ scheme at 2 GeV.

So m_u is many standard deviations from zero. Probably end of story, but some proposals for dedicated tests (Kitano), calibrations (Dine, Draper, Festuccia).

Spontaneous CP Violation: The Nelson-Barr mechanism

Invokes spontaneous CP violation to argue “bare θ" is zero. Constructs a mass matrix such that spontaneous CP breaking gives a large CKM angle (as observed, $\delta = 1.2$) with $\arg \det m_q = 0$.

Bare θ is tree level θ (presumes some perturbative approximation). Must insure that $\theta(\Lambda_{SM})$ is small.

Unlike axion, $m_u = 0$ solutions, no obvious low energy consequences.

Attempts to achieve a setup where θ at the scale Λ_{SM} is extremely small.

Such a structure is perhaps made plausible by string theory, where CP is a (gauge) symmetry, necessarily spontaneously broken. At string scale, $\theta = 0$ a well-defined notion. Some features of the required mass matrices appear, e.g., in Calabi-Yau compactifications of the heterotic string.

Requirements for a successful NB Solution

1. Symmetries: special structures, couplings must vanish.
2. Coincidences of scales: multiple fields required to obtain non-vanishing CKM angle; mass scales (several) required to be close.

Dangers from higher dimension operators; loop corrections. Supersymmetry (at Nelson Barr scale) ameliorates somewhat.

The Peccei-Quinn Symmetry

Peccei-Quinn proposal: replace θ by a dynamical field: $\theta \to \frac{a(x)}{f_a}$

$a \to a + \omega f_a$ is a good symmetry of the theory, *violated only by effects of QCD*. Without QCD, θ can take any value.

In QCD *by itself*, the energy is necessarily stationary when

$$\theta_{eff} = \langle \frac{a}{f_a} \rangle = 0. \tag{6}$$

This is simply because *CP* is a good symmetry of QCD if $\theta = 0$, so the vacuum energy (potential) must be an odd function of θ.

Using chiral symmetry in QCD, the axion potential is:

$$V(a) = m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{a^2}{2 f_a^2} \tag{7}$$

This gives, for the axion mass:

$$m_a = 0.6 \text{ meV} \left(\frac{10^{10} \text{ GeV}}{f_a} \right). \tag{8}$$

Astrophysics: Avoiding excessive production in red giants, white dwarfs, SN1987a: $f_a > 10^{10}\ \mathrm{GeV}$.

Assuming universe was once hotter than a few GeV, axion energy density:

So indeed for $f_a \approx 10^{11}$ GeV and $\theta_0 \approx 1$, the axions come to dominate the energy density of the universe at the approximate time of matter-radiation equality. More careful calculation takes into account the temperature dependence of the axion mass, and yields:

$$\Omega_a h^2 = 0.11\ \theta_0^2 \left(\frac{f_a}{5 \times 10^{11}\ \mathrm{GeV}} \right)^{1.184}. \tag{9}$$

Axion *Quality*

Finally, we turn to a theoretical question: Why are there axions at all? More precisely, why should there be a Peccei-Quinn symmetry, and how good a symmetry does this have to be?

General belief (supported by studies of string theory): *a theory of quantum gravity does not possess (exact) global symmetries.* Then hopeless? No: symmetry might be an accidental consequence of other symmetries.

Example: discrete symmetries. $\phi \to \phi\, e^{\frac{2\pi i}{N}}$. So leading symmetry breaking terms in potential might take the form: $\mathcal{L}_{symm-breaking} = \frac{\phi^N}{M_p^{N-4}}$ But need $N \sim 12$ or larger! Why should this be?

In string theory, provided couplings are small, exponential suppression of symmetry breaking is typically automatic.

The Cosmological Limit on the Scale f_a

Suggests one should think about much higher scale axions. E.g. if reheating temperature after inflation somewhat above nucleosynthesis temperatures (solves other cosmological problems) then can have $f_a \sim 10^{15}$ GeV (perhaps larger?).

Need different strategies for axions searches than the cavity based searches of ADMX. Proposals by P. Graham and others.

Takeaways

1. Dimension $5/6$ operators: sensitive to very high energy scales, if the new physics doesn't have elaborate flavor structure, correlated with what we see at low energies. Could well be first probe of extremely high energy physics (10^3 TeV)?). Improved measurements of d_n, d_e, etc., always welcome.
2. Dimension four: θ. Sensitive to arbitarily high scales. Distinguished in that doesn't contribute to lepton dipole moments.

Directions for simulations and experiments:

Each of the possible solutions suggests research directions.

1. $m_u = 0$: probably ruled out, but continued improvements in lattice simulations, especially tests of θ-dependence of interest.*
2. Nelson-Barr: challenging to build models which are not severely fine-tuned, but the flip side is that such models almost inevitably make predictions close to current limits. If a discovery, new physics nearby, or far away?
3. Peccei-Quinn symmetry: in many ways the most promising solution of strong CP. Here the big puzzle is the *quality* of the symmetry. Simplest explanations as in string theory, point to large values of f_a. So important to pursue current generation of experiments (ADMX) but to be constantly looking for improvements.

The Question: What would you prioritize as problem to solve AND as experimental avenue, for your flavour topic?

Flavor is one of the great problems of particle physics. As a community, we have ideas, but no one compelling picture, and in particular cannot say at what energy scale the physics of flavor should appear.

As a result, some priority should be placed, in my view, on those effects which give the highest energy reach, due to the precision of the experiments. Electric dipole moments enjoy a specal place. Non-zero results in leptons and the neutron would point towards particular energy scales. A dipole moment for the neutron alone would point towards physics of θ.