Snowmass2021 - Letter of Interest

Constraining Physics Beyond the Standard Model using Electric Dipole Moments

EF Topical Groups:)

■ (EF09) BSM: More general explorations
■ (EF05) QCD and strong interactions:Precision QCD

Other Topical Groups:
CompF2, TF05, CF2, RF3

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Collaboration: Precision Neutron Decay Matrix Elements (PNDME) and Nucleon Matrix Elements (NME)

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Abstract: Standard inflationary cosmological scenarios along with the standard model of particle physics are incompatible with the observed excess of baryons over antibaryons in the universe, and need excess CP Violation in theories beyond the standard model. Such CP violation is natural in many extensions of the standard model, and give rise to electric dipole moments, which are likely to be detected in the next decade. To connect their observation, or improved limits, with the fundamental theory, one needs precision experiments along with calculations of the matrix elements of the effective QCD-scale operators within the nucleons and nuclei. Such calculations, however, turned out to be difficult phenomenologically, but, Lattice QCD is showing promise in being able to calculate these quantities. We discuss this promise and the hurdles one needs to overcome in these calculations.

Motivation and Physics Goals: The Standard Model is almost completely symmetric under the simultaneous operation of spatial reflection and charge conjugation of all the particles. This is currently known to be violated only by the fundamental Yukawa interactions in the quark sector that is irreducibly complex when the number of families is greater than two[17], and possibly by a similar phase in the neutrino sector[21].

The observed universe has $6.1^{+0.3}_{-0.2} \times 10^{-10}$ baryons for every black body photon[4], whereas in a baryon symmetric universe, we expect no more that about 10^{-20} baryons for every photon[18]. The observed excess of baryons over antibaryons in the universe, however, is incompatible with the standard cosmological theories. If we assume that this excess was present in the initial matter forming the universe, then the universe becomes matter-dominated instead of inflating as needed to explain its observed homogeneity[11]. On the other hand, creating this excess needs evolution out of thermal equilibrium, baryon number violation, and C and CP violation[25]. The standard model has all the ingredients, but their magnitude is too small to explain the observed excess of baryons.

CP violation is, however, natural in extensions of the standard model: without an *a priori* constraint, the couplings are complex, and cannot be rotated away. In extensions that do not introduce new naturalness problems, they arise suppressed by a mass scale of a few TeV. Such new sources of CP violation, if coupled to the QCD sector, generically give rise to electric dipole moments (EDMs) of neutrons, protons, nuclei, and atoms. Since the standard model contributions to these EDMs is 3–4 orders of magnitude below current bounds[26], they are clean systems to probe this new physics.

There are a number of experiments that are ongoing or planned[22] that are expected to observe or improve the EDM bounds in various systems by 1–2 orders of magnitude beyond the current limit[2] of $|d_n| < 1.8 \times 10^{-26}$e-cm in the near future. Recent calculations[7;8;15] have shown that for a number of specific BSM models, the bounds implied by such an improvement will be stronger than the expected accelerator bounds, provided the uncertainties in the relevant nuclear matrix elements are reduced. Importantly, phenomenological calculations have large systematic uncertainties, often by an order of magnitude, which limits the impact of experimental bounds.

This, thus, opens up a clear target for a joint experiment-theory program to elucidate novel sources of CP violation.

Effective field theory: One can study the BSM effects model-independently using Effective Field Theory. At dimension four, there is only one operator: the gluonic topological term (the strong CP violating Θ-term)[13]. The absence, or smallness, of this term is not understood, and a Peccei-Quinn mechanism is often invoked to explain this. At dimension five, there are two operators: the quark EDM and the quark chromo-EDM. Both of these violate the $\mathrm{SU(2)_L \times U(1)_L}$ symmetry of the weak interactions. These appear as effective operators below the scale of weak symmetry breaking from dimension six operators including the Higgs field above that scale. Moreover, in many extensions of the standard model, such chirality-violation is small in the light-quark sector, so their phenomenological impact might be as small as the dimension six operators. At dimension six, one there are the gluon chromo-EDM, which is also called the Weinberg operator, and a set of four-fermion operators.

Lattice QCD calculations: The hadronic EDMs generated by these effective operators can be analyzed at the leading order using chiral perturbation theory in terms of various low-energy constants[12;23]. These are the EDMs of the proton and neutron and CP-violating πNN and $NNNN$ couplings. The neutron and proton EDM from the quark EDM is known[15] to about 10%. Calculations are underway for the topological charge[14], Weinberg operator, and the chromo-EDM operator. These calculations will have a phenomenological impact[8] even if the determination is only precise up to a factor of about 1.5–2. The statistical precision of their calculation is already much better than this. What one needs is control over the systematics, especially subtraction of excited state contributions, the chiral-continuum extrapolation, and renormalization.

Light excited states of the nucleon in finite volume lattice QCD are difficult to isolate[16], and the $N\pi$ states, in particular, have been shown to have a large impact on the extraction of some matrix elements. Preliminary estimates from chiral perturbation theory indicates that this is likely to be the case for the neutron EDM contribution from the topological term, and may be for the other operators as well. As a community, we need to develop robust and systematically improvable ways of getting these under control. Second, the chiral-continuum extrapolations show a large dependence on the chosen number of correction terms (extrapolation ansatz). Some of these problems may be cured by higher precision lattice data. In addition, theoretical insight from chiral perturbation theory and comparison between different fermion discretizations will also be important.

A final aspect of the Lattice QCD calculation of EDMs involves obtaining a finite result, and converting this result to schemes such as MS-bar routinely used in continuum calculations to connect low-energy observable to models of new physics. This is typically achieved by introducing intermediate non-perturbative renormalization schemes, such as variants of the regularization independent momentum subtraction (RI-MOM) scheme[20]. RI-MOM schemes for the dimension-five quark chromo-EDM operator and dimension-six three-gluon operator are available[6;10], along with the one-loop conversion factors to MS-bar. The complexity of mixing structure in these off-shell schemes calls for future analyses of CP-odd dimension-five and -six operators based on the gradient flow[19], for which a first study has appeared[24].

Constraints from Colliders: The new sources of CP-violation that give rise to EDMs at low-energy can also manifest themselves in high-energy colliders. The Standard Model Effective Field Theory provides a systematic framework to organize CP-violating interactions at the electroweak scale, to study their collider signatures and to compare the sensitivity of high- and low-energy experiments. In recent years, we have studied CP-odd operators in the SMEFT, with particular attention to the Higgs, top and electroweak gauge boson sectors[3;7–9]. In general, EDMs provide constraints that are very competitive with colliders. While in the first two LHC runs we mainly focused on inclusive observables such as total cross sections or signal strengths, the integrated luminosity at the LHC Run 3 and at the High-Luminosity LHC will allow us to study differential distributions, which could provide more direct evidence of CP violation[1;5;27;28]. An analysis of CP-odd differential distributions in the Higgs and top sectors, assessment of the sensitivity of the LHC to CP-odd SMEFT operators, and examination of the complementarity of these observables with EDMs are currently planned.

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