EDM Searches

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Abstract. Searches for permanent electric dipole moments of fundamental particles and systems with spin are among the most sensitive probes for physics beyond the Standard Model of particle physics. Many experimental efforts are under-way. This proceedings article presents a compilation of the presently ongoing experiments and those planned for the foreseeable future.

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PACS: 13.40.Em Electric and magnetic moments, 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries

RELEVANCE OF SEARCHES FOR PERMANENT EDM

Searches for electric dipole moments (EDM) of fundamental particles and systems with spin (like neutrons, atoms, molecules, protons, deuterons, muons, ...) are considered to be amongst the most important particle physics experiments at the low energy, high precision and intensity frontier: see e.g. [1, 2, 3]. They provide an alternative route to new physics, which is complementary to searches at high energy colliders. EDM searches provide the most sensitive tests of non-standard time reversal invariance violation and, by the CPT-theorem, of CP-violation. Generically, assuming a large CP-violating phase, fundamental fermion EDM today test new physics at mass scales around 10-100 TeV. A very recent theory review together with a listing of experimental efforts can be found at [4].

TABLE 1. The present best EDM limits of their kind: bare nucleon, lepton, diamagnetic atom, paramagnetic atom, and molecule. The extraction of e.g. the electron or the proton EDM limits assumes a single source of CP violation, i.e. other particle EDM or CP violating interactions between quarks and electrons to vanish.

System	upper limit [$e$cm]	Reference	Comment
n	2.9×10^{-26} 90% C.L.	[8]	direct limit
μ	1.9×10^{-19} 95% C.L.	[9]	direct limit
^{199}Hg	3.1×10^{-29} 95% C.L.	[7]	best direct EDM limit of any experiment; best indirect limit for proton $d_p < 8 \times 10^{-25} e$cm
^{205}Tl	9×10^{-25} 90% C.L.	[5]	used to set a limit for the electron $d_e < 1.6 \times 10^{-27} e$cm
YbF	1.1×10^{-22} 90% C.L.	[6]	used to set a limit for the electron $d_e < 1.05 \times 10^{-27} e$cm

The observation of any new CP-violating physics would be a very significant discovery. Interpretation of the experimental results requires theoretical treatment on various levels. For instance, the most sensitive limits on the EDM of the electron come from experiments with paramagnetic atoms (e.g. ^{205}Tl [5]) and molecules (e.g. YbF [6]). These are sensitive both to the intrinsic electron EDM and to CP-violation in the electron-quark interaction. Sophisticated atomic and molecular calculations are required to account for these interactions. Similary, when using diamagnetic atoms (e.g. ^{199}Hg [7]), atomic and nuclear theory are both required to extract nucleon EDM or even quark and colour EDM. Somewhat easier but still model dependent is the extraction of the fundamental fermion EDM from that of the neutron [8], proton or even deuteron measurements. Interestingly, today, of the fundamental fermions only the muon provides an EDM limit from a direct measurement [9]. The present best experimental limits are compiled in Table 1. For a review of atomic symmetry violation see e.g. [10], a few examples of molecular calculations are [11, 12, 13]

The known CP-violation of the electro-weak standard model produces EDM only via higher-order loop contributions. These are five orders of magnitude too small to be detected for current experimental sensitivities in case of the neutron, eleven orders of magnitude for the electron and even more for other particles like muons or taus. However, most new physics scenarios include additional sources of CP-violation which quite naturally could account for the observed baryon asymmetry of the universe, and they typically predict much larger EDM: The experimental EDM bounds thus tightly constrain the parameter space of many such new-physics models and theories. For instance, the fact that no fundamental EDM has been found so far excludes naive Supersymmetry models and is known as the 'Susy CP-problem'. An example showing how the CP phases in a particular model can be constrained by combining experimental inputs from Table 1 is displayed in Fig. 1 [14].

For hadronic probes, like neutrons and nuclei, EDM can also be induced by the so called Θ-term of QCD. These EDM experiments can thus also be considered to be measurements of Θ, which arguably is the last unmeasured parameter of the Standard Model. The fact that hadronic EDM have not been found so far limits Θ to be extremely, perhaps unnaturally small (of order 10^{-10}) which is termed the 'strong CP-problem'.

The next round of planned experiments allows for a few orders of magnitude improved sensitivity, thereby closing further the gap to the electro-weak standard model EDM. Even in case of non-observation of EDM this might, e.g., completely rule out already electro-weak baryogenesis in MSSM models [15].

PRESENT AND FUTURE EXPERIMENTAL EFFORTS

Figure 2 displays the presently ongoing and planned experimental efforts for searches for permanent electric dipole moments.

Several neutron EDM projects are progressing around the world. These are being pursued in medium-size, often international collaborations grouped around ultracold neutron sources in operation, under construction or planned. Searches for EDM of atomic or molecular systems are mostly performed by smaller size teams, the same is true for the searches for an electron EDM in solids. Larger projects than the neutron EDM efforts are proposed and being pursued for the search of the EDM of the proton and the deuteron using novel storage ring methods. A rather complete listing of these projects along with according links to project descriptions for further information and reference

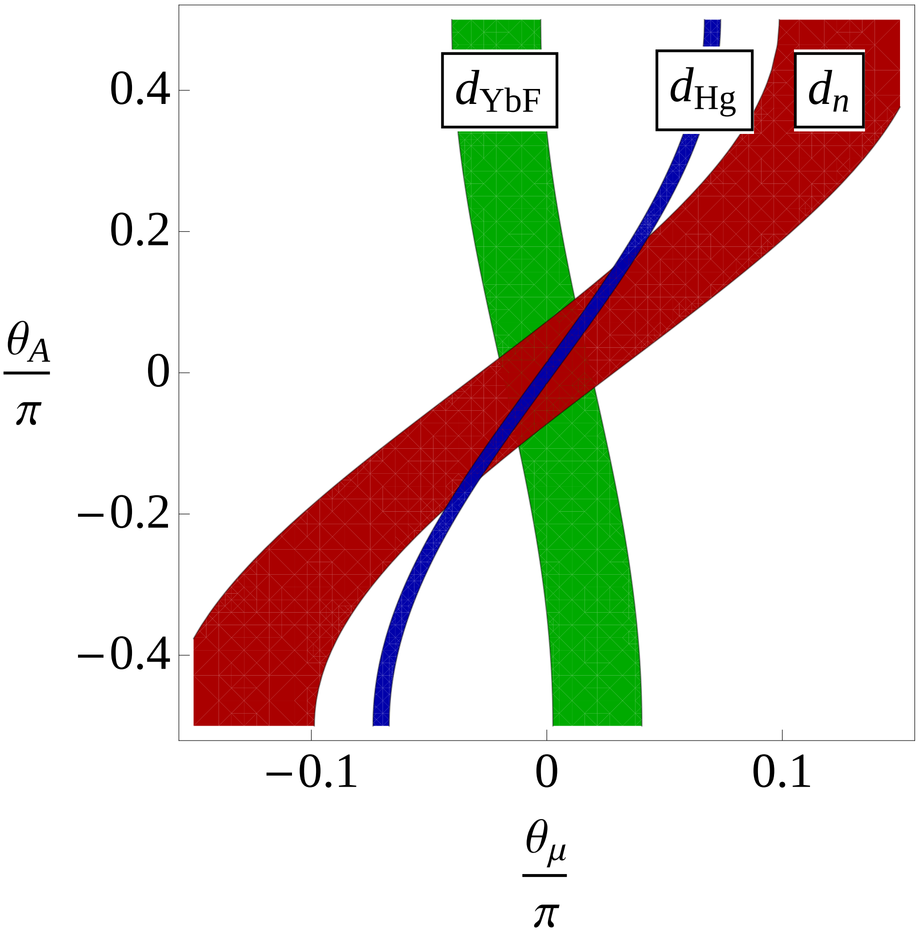

FIGURE 1. The plot shows the power of combining the results of different best EDM experiments (see Table 1). The showcased Susy example is a 1-loop calculation with O(1)-phases and assumes a generic mass scale of 1 TeV for all contributing superpartners sfermions (the stop mostly affects 2-loop contributions and can still be relatively light) and $\tan\beta$=3. In that case, similar limits apply as in the cMSSM and the scenario is under pressure now from direct Susy mass limits [14]. The plot has been kindly provided by A. Ritz and updates an earlier version in [2].

has been collected [18]. The field of EDM searches is still in a phase pushing towards the discovery of the first finite permanent EDM. Therfore it is most important to pursue many different efforts regarding the source of CP violation but also regarding different technologies in order to further develop and establish the most sensitive and powerful techniques. Obviously, improving EDM limits severely constrains parameter spaces of many models of CP violation. If finite EDM will eventually be discovered, certain sets of EDM measurements may allow to disentangle the underlying physics. We may for instance expect the neutron EDM in combination with proton and deuteron EDM to decide the question whether or not the QCD Θ-term is at work. Various combinations of nuclear, atomic and molecular EDM might establish how an EDM of the electron

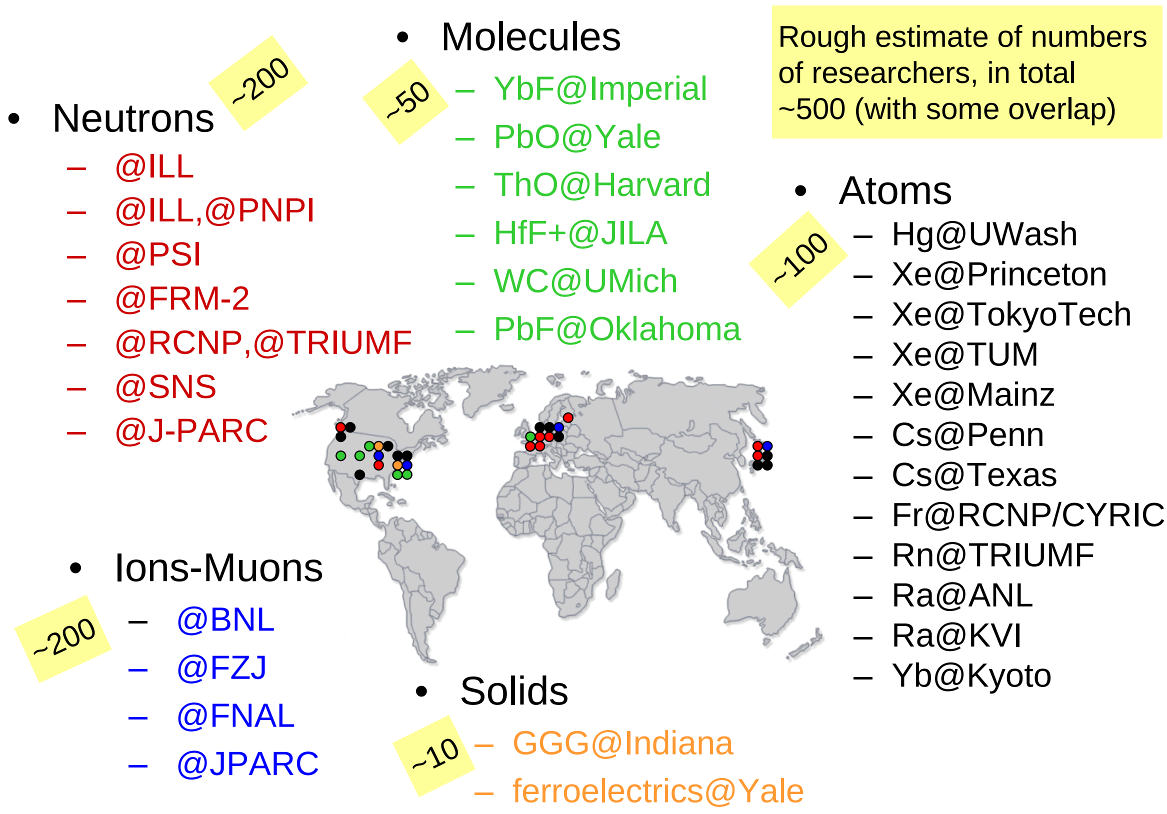

FIGURE 2. List of known EDM efforts in the various categories. The number of researchers in the field has not been thoroughly counted but only roughly estimated. References to all these efforts are found at [18].

and CP violating interactions of leptons and quarks appear in the correct theory. Also the question whether or not the muon EDM is perhaps much larger than assumed from simple mass scaling from the electron EDM will have to be answered at some point. Here, the next step will come as a by-product of the next muon (g-2) experiments.

Given the number of efforts, the new ideas and proposals and the competition in the growing field, we may expect major experimental progress over the next decade. Important cross-disciplinary efforts are developing connecting spin physics, magnetometry, surface science, chemistry, accelerators, high-power targets, cryogenics, non-magnetic materials, and many more fields. At the same time, it will be important to further develop the theoretical methods such that the dependence of all experiments on the underlying set of CP violating parameters can be established and calculated reliably. It is much beyond the scope of the present article to review the efforts in theory performed over the past years, see e.g. [4] for a list of references. However, several new activities have been started, both, to improve the calculation of EDM in models beyond the standard model of particle physics and to improve the underlying 'standard' theory calculations dealing with the complexity of the involved systems. It is impossible to give a fair account here, but the reader is, e.g., referred to [16, 17] illustrating some of the statements just made. Theory must include and improve on very involved atomic, molecular and nuclear calculations because the experimentally most sensitive systems will not necessarily be the easiest to treat in theory. This way, guidance should be provided for further experimental efforts with the aim to concentrate on the most important, 'complete' set of experiments.

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