Electric Dipole Moment Experiments

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Electric Dipole Moment (EDM) searches in neutrons, electrons, diamagnetic atoms and elsewhere, are searches for new physics not contained in the Standard Model that are expected to turn up in one or more than one of these systems. There is however a risk of false negatives, so an EDM limit set by a single experiment should not be relied upon to favor one model over another: confirming experiments are needed, particularly for the diamagnetic atom EDM and the electron EDM. Suggestions to reduce the risk of false negatives and false positives are included.

I. EXECUTIVE SUMMARY

Discovery of an electric dipole moment (EDM) would be direct evidence of new physics. Despite the large quark sector $\mathcal{CP}$ violation, the Standard Model does not generate experimentally observable electric dipole moments (EDMs), allowing their possible discovery to serve as evidence of new physics. Standard Model Extensions contribute to EDMs because they contain new particles and couplings with new $\mathcal{CP}$-violating phases.

Experiments to search for neutron, electron, and diamagnetic atom EDMs, and maybe others, are all needed. An EDM could be found in the quark sector, lepton sector, in interactions between quarks and leptons or in any combination of these. Neutron, electron and diamagnetic atom EDM experiments are needed to address these possibilities and together they constrain Standard Model Extensions far better than can any one or two experiments. If an EDM is discovered in one system, results in others will be needed to distinguish between theoretical models, such as to distinguish a neutron EDM that arises from $\theta_{QCD} \neq 0$, for example, from a neutron EDM arising from Supersymmetry.

Confirming experiments are needed, particularly for the diamagnetic atom EDM and the electron EDM. It is a widely followed practice that important experimental results be confirmed by a another group, preferably at a different laboratory or facility, and preferably using a different experimental method. This would be the standard of experimental evidence needed to confirm any major discovery. Why would one accept a lower standard of proof to discredit a major theory that is widely anticipated and has been expounded upon in thousands of journal articles?

The history of laboratory experiments looking for parity non conservation predicted by the (Glashow)-Weinberg-Salam Model shows a large risk of false negatives. EDM experiments may be at even greater risk of false negatives.

The following should be considered:

- A wider range of EDM experiments, particularly diamagnetic atom EDM and electron EDM experiments.
- More interaction between EDM experimenters across different experiment types is needed, as is coordinated or shared R & D.
- EDM experiments should be published as full length articles in well refereed, open access physics journals, and experiments should include a sensitivity test.

II. THE UTILITY OF ELECTRIC DIPOLE MOMENT (EDM) EXPERIMENTS

Absent a mechanism to suppress EDMs of fundamental particles, their discovery should be anticipated.

Permanent EDMs of fundamental particles arise through radiative corrections that involve $\mathcal{CP}$ violation. Although the $\mathcal{CP}$-violating phase in the quark sector of the Standard Model is not small, the Standard Model's special structure

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allows its EDMs to arise only from diagrams with so many loops, with so many virtual particles of large mass, and so many other special cancelations that the EDMs, though nonzero, are predicted to be orders of magnitude below the reach of any experiment yet conceived.

Standard Model Extensions generically possess new particles with new sources of $\mathcal{CP}$-violation. They do so because the $\mathcal{CP}$ violation already in the Standard Model has effects too small to explain the observed excess of matter over antimatter in the universe, and because efforts to embed the Standard Model in larger theoretical structures, such as supersymmetry, have so far produced overwhelmingly only theories with large numbers of $\mathcal{CP}$-violating phases none of which have any reason to be small.

The Minimal SuperSymmetric Standard Model (specifically MSSM-124), for example, possesses no fewer than 40. The new particles and phases typically cause EDMs at one-loop, not multi-loop, order, and presently claimed EDM limits are already about a factor of 100 below simple Supersymmetry estimates that use superpartner masses of 100 GeV and $\mathcal{CP}$-violating phases of order unity[8-14].

The great strength of a tighter limit on the electric dipole moment is not just that it will constrain Supersymmetry, or any one specific model, but that it will constrain *all* proposed theories, including ones yet undreamed of. And even if a direct accelerator search for a new particle succeeds, and provides evidence of a new $\mathcal{CP}$-violating interaction, measurement of an EDM will likely remain useful, since it is likely that the combination of theoretical parameters probed in accelerator experiments will be orthogonal to the combination that is probed in an EDM. However much information might become available from accelerators, experiments on EDM will be a cheap source of more; and indeed, information about EDMs from cheap experiments may instead inform the construction of very expensive accelerators. The contribution to an EDM from a new particle typically scales as the inverse square of the particle mass, and to search for a new particle it may well prove easier to tighten the limit on an EDM by a factor of 9 than to raise the center-of-mass energy of present accelerators by a factor of 3.

III. ELECTRON, NEUTRON, AND DIAMAGNETIC ATOM EDM EXPERIMENTS ARE ALL NEEDED

It is becoming more difficult to maintain a Minimal Supersymmetric Standard Model (MSSM) and not have observed EDMs[1], especially when EDM limits on the electron, the neutron, and diamagnetic atoms are used together to constrain adjustments to CP-violating phases [2]. Present electron EDM results [3–5] are about a factor of 100 below simple Supersymmetry EDM estimates that use super-partner masses of 100 GeV and $\mathcal{CP}$-violating phases of unity [6–12], and are not in complete agreement with some models that use super-partner masses of one TeV [2]. How well the experiments constrain the MSSM depends on the details of the model. Not all authors find identical constraints[13].

The advantages of searching for an EDM in multiple systems are:

- Together, electron, neutron and diamagnetic atom EDM experiments presently constrain Supersymmetry better than do any one or two of these. Using only neutron and electron EDM experiments, it was possible to maintain large $\mathcal{CP}$-violating phases and small superpartner mass limits by arranging cancellations [14, 15]. But when the diamagnetic atom EDM experiment was added, the largest $\mathcal{CP}$-violating phases (and smallest superpartner masses) were no longer allowed [7–9, 16].

- If non-Standard Model EDMs exist, we do not know if they will easiest to observe in the electron or other lepton[1], the neutron, or a diamagnetic atom.

- If an EDM is discovered in one system, results in others will be needed to distinguish between theoretical models. An electron EDM limit will help to distinguish a neutron EDM that arises from θ_{QCD}, for example, from one arising from Supersymmetry.

[1] An electron EDM is expected to be smaller than a muon EDM by m_e^2/m_μ^2, where m_e and m_μ are the mass of the electron and muon respectively. The higher sensitivity of electron EDM experiments more than make up for this difference. However, one proposed mechanism for a muon EDM [17] does not result in the expected EDM ratios, making muon EDM and electron EDM experiments potentially complementary.

IV. EDM NULL EXPERIMENTS NEED CONFIRMATION

A. EDM Limits and Standard Model Extensions

It is a widely followed practice that important experimental results be confirmed by a another group, preferably at a different laboratory or facility, and preferably using a different experimental method. This would be the standard of experimental evidence needed to confirm any major discovery. Why would one accept a lower standard of proof to discredit a major theory that is widely anticipated and has been expounded upon in thousands of journal articles?

Table I shows the experimental limits set for diamagnetic atoms, the electron, and the neutron in S.I. units of 10^{-50} C·m. (To convert C·m to e·cm divide by 1.6×10^{-21}). The EDM limits are arranged from lowest (best) to higher limits and arranged by type of experiment. The lowest experimental limit that is confirmed by another group using a different experimental method is shown in bold.

TABLE I: EDM Limits & Confirmed Limits

Diamagnetic Atom EDM

Year	Limit ($\times 10^{-50}$C·m)	System	Group	Ref.
2009	5.0	^{199}Hg	Seattle	[18]
2001	34	^{199}Hg	Seattle	[19]
1995	140	^{199}Hg	Seattle	[20]
1993	210	^{199}Hg	Seattle	[21]
1987	3500	^{199}Hg	Seattle	[22]
2001	**640**	**^{129}Xe**	**Michigan**	[23]
1984	2200	^{129}Xe	Seattle	[24]

Electron EDM using Molecules

Year	Limit ($\times 10^{-50}$C·m)	System	Group	Ref.
2014	14	ThO	Acme	[3]
2011	**170**	**YbF**	**Imperial**	[4]
2013	2700	PbO	Yale	[25]
2002	3400	YbF	Imperial	[26]

Electron EDM using Atoms

Year	Limit ($\times 10^{-50}$C·m)	System	Group	Ref.
2002	220	Tl	Berkeley	[5]
1994	640	Tl	Berkeley	[27]
1990	1800	Tl	Berkeley	[28]
1989	**14000**	**Cs**	**Amherst**	[29]

Neutron EDM[a]

Year	Limit ($\times 10^{-50}$C·m)	Facility	Group	Ref.
2006	4600	ILL	UK, Fr	[30]
2014	**8800**	**ILL**	**Russ, Fr**	[31]
1999	10000	ILL	UK, Fr	[32]
1992	**16000**	**LNPI**	**Leningrad**	[33]
1990	96000	ILL	UK, US, Fr	[34]

[a] If the confirming experiment is not restricted from being done at the same facility, then the confirming experiment becomes Ref. [31] (2014).

Constraints on the Minimal Supersymmetric Standard Model from EDM experiments are considerably weakened if one chooses limits that have been confirmed by another group using a different experimental method. For the electron EDM and the diamagnetic atom EDM, confirmed EDM limits are from *one to three orders of magnitude higher* than the lowest EDM limit. For the neutron EDM, the confirmed limit is higher than the lowest limit by about a factor of two. This is shown in Table I.

For diamagnetic atoms, the confirmed experiment is the 2001 Michigan ^{129}Xe experiment[23] with a limit about two orders of magnitude higher than the most recent Seattle ^{199}Hg experiment[18]. For the electron, the confirmed experiment is the Imperial College YbF experiment[26] with a limit about an order of magnitude higher than the recent Acme ThO experiment[3]. If one treats electron EDM experiments using molecules separately from electron EDM experiments using atoms[2], then the confirmed electron EDM experiment using atoms is the 1989 Amherst College Cs experiment [29], which is two orders of magnitude higher than the 2002 Berkeley Tl EDM experiment [5] and three orders of magnitude higher than the Acme experiment[3].

B. A Cautionary Tale from the Discovery of Weak Neutral Currents

To understand the existential risk from not setting limits through confirmed experiments, anchored by detailed and reliable calculations, one need only look at the discovery of weak neutral currents. In addition to neutrino experiments, the effects of weak neutral currents show up in atoms and nuclei, and in high energy electron scattering as parity nonconservation (PNC). Evidence for weak neutral currents was reported in 1973 from the CERN Gargamelle neutrino experiment [36]. Laboratory experiments looking for PNC followed.

An initial string of four or five laboratory scale experiments followed this, reporting null results with no laboratory experiments supporting the existence of PNC and by implication, weak neutral currents. This might have discredited the Weinberg-Salam theory and delayed (or worse) the discovery of the Z_0 had not strong evidence of weak neutral currents already been reported in 1973 from the Gargamelle neutrino experiment [36] and again in 1978 from the observation of PNC in inelastic electron scattering at SLAC [37, 38]. The chronological record is instructive:

- In 1977 two laboratory experiments reported null results from measurements of PNC optical rotation in bismuth[39, 40]. Baird et al. used the 648 nm transition and, in 1977, reported in Phys. Rev. Lett.[39],

  > We conclude by noting that our null result is in disagreement with the theoretical prediction. A similar result is found in the accompanying paper which describes a related experiment on the 876-nm . . . transition in atomic bismuth [40].

  In addition to the papers in Phys. Rev. Lett., the authors jointly published a paper in Nature[41].

- In 1978, searching for PNC effects in the nucleus, Barnes et al.[42] reported that

  > The circular polarization of the γ rays from the $1.08 \rightarrow 0.0$ MeV transition of ^{18}F has been measured to be ... a value significantly smaller than predicted by recent calculations which include the effects of weak neutral currents.[3]

- In 1978 Barkov and Zolotorev were able to observe the predicted parity nonconservation in optical rotation in bismuth[44] by measuring seven hyperfine components of the 648 nm line, three of which do not couple in parity violation (and thus provide a test of systematic errors). Later that year Prescott et al, published an observation of "Parity non-conservation in inelastic electron scattering" using a polarized electron beam at SLAC [37, 38].

- In 1979 Conti et al. [45] published a "Preliminary Observation of Parity Nonconservation in Atomic Thallium" and in other atomic PNC experiments in 1981 and 1982 PNC, consistent with predictions of the Weinberg-Salam Model, was consistently observed [46–48].

- In 1982, Elsener et al.[49] reported that

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[2] A recent field theory calculation [35] has shown the enhancement factor in alkali atoms and thallium to be consistent with previous calculations.

[3] Later that year, Snover et al. [43] searched for parity nonconserving circular polarization from the $2.789 \rightarrow 0.0$ MeV transition in ^{21}Ne and found an even smaller PNC effect.

> ... the first excited state of polarized ^{19}F (110 keV) has been measured with particular care to avoid systematical errors and is found to be ... several times smaller than the predictions of theoretical calculations based on the Weinberg-Salam theory.

- In 1987, four years after the discovery[4] of the Z_0, Page et al. reported further measurements on circular polarization of the 1.08 MeV γ from ^{18}F [51] and (again) found:

> The present result for the weak pion-nucleon coupling strength is ... which is significantly smaller than recent theoretical predictions based on the Weinberg-Salam model.

C. This Time is Different?

The present experimental environment for EDM experiments differs from the 1970's and early 1980's experimental environment for laboratory PNC experiments in that:

- Present EDM experiments are probably more difficult than 1970's era PNC experiments because of the need for ever increasing experimental sensitivity and the need for ever better suppression of systematic effects.
- There are no High Energy Physics Experiments that can discover an EDM or even suggest a value for an EDM. The claimed sensitivity of already completed experiments suggests a limit on superpartner masses that is at or above the range of the LHC. Laboratory experiments are performing largely without a net.

V. A FEW STEPS TO CONSIDER

1. If the theory community wants to see its predictions faithfully tested, it needs to advocate for, and support a wider range of diamagnetic atom and electron EDM experiments, done by adequately resourced multi-investigator groups with a strong commitment to the discipline.
2. EDM experimenters need to appreciate that they need competent competitors who can furnish Post Docs, hire former students, solve common problems, and confirm your EDM discovery while you are still alive.
3. Most neutron, electron, and diamagnetic atom EDM experiments use similar techniques and have very similar systematic effects. A series of experimental workshops and possibly shared R & D can help overcome common problems while saving time and money.
4. Professional development for EDM experimenters needs to be considered. Who can afford to devote most of their time and effort to an experiment that yields one paper every four years? And if there is no such focus, then who is lying awake at night worrying about the experiment?
5. EDM experiments should be published as full length articles in open access physics journals, not just in letters journals. Editors should assign more than a single referee. This is not a great burden. Referee overwork is not being caused by the six-experiment-per-decade load of successfully completed EDM experiments.
6. EDM experiments should include a sensitivity test. In most cases this can be a small synchronous magnetic field added to, or replacing, the electric field.
7. Successful EDM experiments require development of specialized technologies. Their development, with appropriate funding, needs to precede funding for construction of the actual experiment, as does a through understanding of the systematic uncertainties which evolve with each new technology.

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[4] The Z_0 was discovered in 1983 at the CERN SPS collider in both the UA1 and UA2 detectors. The UA2 detector was a second detector of a different design[50] from UA1, built and operated by a different and independent experimental group at considerable additional expense to CERN.

VI. ABOUT THE AUTHORS

Harvey Gould is working on his fifth electron EDM experiment. Three experiments using Cs and Tl set or tied the EDM upper limits and the fourth experiment, a proof-of-principle experiment, was the first laser-cooled atom EDM experiment. When not working on EDM experiments he has performed experiments at the Brookhaven AGS, the CERN SPS, and the LBL Super-HILAC and Bevalac where, in 1983, he made the first observation of U^{92+}.

Charles Munger, in addition to performing the first laser-cooled atom EDM experiment, has published a comprehensive analysis of systematic effects in fountain electron EDM experiments. He has also done experiments at the LBL Bevalac, at SLAC with the Mark II Collaboration, and at FNAL, where he used he antiproton accumulator to produce antihydrogen.

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