Motivation for Proton and Deuteron EDM Measurements

Modern interest in elementary particle and bound-state electric dipole moments (edms) stems from the pioneering work of Normal Ramsey and his collaborators [1]. Their more than 50-year quest to find a neutron edm anticipated parity (P) and time-reversal (T or CP) violation, necessary ingredients for the existence of a non-zero edm. Over the years, improvements in the bound on d_n have been used to rule out or severely constrain many models of CP violation, a strong testament to the power of sensitive null results.

As a result of those efforts, the neutron edm bound currently stands at

$$\left|d_n\right| < 3\times10^{-26}\,\mathrm{e}\cdot\mathrm{cm} \tag{1}$$

Complementary to the bound, elegant (neutral) atomic physics experiments have obtained improved atomic edm constraints. Examples are

$$\left|d_{Tl}\right| < 9\times10^{-25}\,\mathrm{e}\cdot\mathrm{cm} \tag{2}$$

$$\left|d_{Xe}\right| < 6\times10^{-28}\,\mathrm{e}\cdot\mathrm{cm} \tag{3}$$

$$\left|d_{Hg}\right| < 3.1\times10^{-29}\,\mathrm{e}\cdot\mathrm{cm} \tag{4}$$

Those bounds have been used to constrain "new physics" scenarios and provide the indirect charged particle bounds (from *Tl* and *Hg* respectively)

$$\left|d_e\right| < 1.6\times10^{-27}\,\mathrm{e}\cdot\mathrm{cm} \tag{5}$$

$$\left|d_p\right| < 7.9\times10^{-25}\,\mathrm{e}\cdot\mathrm{cm} \tag{6}$$

Although the indirect $|d_p|$ bound from atomic experiments has improved considerably over recent years, it is still a factor of 26 worse than $|d_n|$ and not really competitive. Here, we discuss an experimental opportunity, provided by storage ring technology, to push the direct measurement of d_p and d_D (deuteron) to 10^{-29}e·cm sensitivity, an improvement by nearly 5 orders of magnitude. Such dramatic improvement is made possible by new ideas and techniques described in this document.

What would we learn from the measurement of a non-zero edm? The standard $SU(3)_C\times SU(2)_L\times U(1)_Y$ model predicts non-vanishing edms; however, their magnitudes are expected to be unobservably small $\left|d_e^{SM}\right| < 10^{-38}\,\mathrm{e}\cdot\mathrm{cm}$ and $\left|d_N^{SM}\right| < 10^{-32}\,\mathrm{e}\cdot\mathrm{cm}$, $N=n,p$. Hence, discovery of a non-zero edm between the current bounds and standard model predictions would signal "new physics" CP violation. Uncovering such a phenomenon could prove crucial in understanding the matter-antimatter asymmetry of our universe which seems to require (suggest) new large sources of CP violation beyond standard model expectations. That fundamental connection with the origin of our very existence coupled with the popularity of well motivated "new physics" scenarios such as supersymmetry (SUSY) with potentially large new sources of CP violation make searches for edms exciting and at the forefront of high energy and nuclear physics. Indeed, it is anticipated that the next generation of edm experiments with several orders of magnitude improved sensitivity may be on the verge of a major discovery with far reaching implications.

Of course, several new neutron edm experiments are already mounted worldwide. They aim to eventually approach $|d_n| \sim 10^{-28}\,\mathrm{e}\cdot\mathrm{cm}$ sensitivity. At that level, the $\bar{\theta}$ parameter of QCD, SUSY phases, Left-Right symmetric models, multi-Higgs scenarios etc. are being probed. With that backdrop, what is the added value of proton and deuteron edm experiments with goals exceeding the d_n searches?

The obvious answer is that storage ring studies aim for $|d_p|$ and $|d_D|$ sensitivities of 10^{-29} e·cm, more than an order of magnitude beyond $|d_n|$ expectations. Hence, they represent the possibility of significant improvement beyond already forefront efforts. However, even at lower 10^{-28}e·cm level, roughly comparable to d_n, they are extremely complementary to d_n and will be of crucial follow-up importance should a non-zero value of d_n or any other edm be measured.

To put d_n, d_p and d_D into perspective, we note that a priori, all are independent and could have significantly different values. Only when interpreted within the context of a specific theoretical framework, do their values become related and comparison is meaningful. If d_n is found to differ from zero, d_p and d_D will prove crucial in unfolding the new source of CP violation responsible for it. To sort out its structure, the I=1 and 0 isospin combinations

$$d_N^{I=1} = \left(d_p - d_n\right)/2 \tag{7}$$

$$d_N^{I=0} = \left(d_p + d_n\right)/2 \tag{8}$$

along with d_D (which samples various isospin effects) will be complementary.

To illustrate the combined utility, we consider several examples.

1) The QCD CP Violating $\bar{\theta}$ Parameter

The $\bar{\theta}$ CP-violating parameter of QCD can be set to zero in lowest order, but will reemerge from high scale physics via loop level contributions to the quark mass matrix. For nucleons, one expects from leading chiral logs (*ln* m_p/m_π terms) the isovector relation

$$d_n \simeq -d_p \simeq 3\times10^{-16}\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm} \tag{9}$$

From the bound on equation (1), the restrictive constraint $\bar{\theta} < 10^{-10}$ already follows. The sensitivity will improve to better than 10^{-13} if the storage ring goal of d_p~10^{-29}e·cm is achieved. More interesting, should a non-vanishing d_n be measured, it will be necessary to determine d_p to see if the isospin relation of equation (9) is respected. That will, of course, require a measurement of d_p with sensitivity comparable to d_n. Also, even a primarily isovector $\bar{\theta}$ effect, $|d_D|$ is expected to be smaller than $|d_N|$ due to leading log cancellations between d_n and d_p but not zero. Indeed, from non-logarithmic contributions, one roughly anticipates

$$d_D\left(\bar{\theta}\right)/\,d_N\left(\bar{\theta}\right) \approx 1/3 \tag{10}$$

Confirming or negating $\bar{\theta}$ effects will certainly require measurements of d_n, d_p and d_D.

2) Supersymmetry

Supersymmetry (SUSY) and the new particles associated with it (sparticles) represent a popular, well motivated extension of the standard model. If real, it suggests that a plethora of new particles will be revealed at the LHC. New CP phases associated with SUSY interactions could lead to electromagnetic quark edms, d_q with $q=u$ or d, as well as quark color edms, d_q^c, all of which are rather independent. One expects [2]

$$d_n \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right) \tag{11}$$

$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right) \tag{12}$$

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right) \tag{13}$$

or in terms of I=1 and 0 components

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right) \tag{14}$$

$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right) \tag{15}$$

Notice that d_D is very sensitive to the isovector combination $d_u^c - d_d^c$ due to the 2-body pion exchange and represents our most sensitive probe of that quantity by more than an order of magnitude. On the other hand $d_N^{I=1}$ is more sensitive to the electromagnetic d_u-d_d while $d_N^{I=0}$ would determine the isoscalar electromagnetic and color combination in equation (15). Although measurements of d_n and d_p and d_D might not uniquely determine the underlying "new physics" source of CP violation; they will take us quite far in unfolding its structure.

An alternative to the above light quark scenario might be one dominated by heavy quark edm effects. In that case, one would expect isoscalar dominance and

$$d_n \simeq d_p \tag{16}$$

$$d_D \simeq d_p + d_n \tag{17}$$

To test those relations, requires measurements of d_n and d_p and d_D with similar sensitivity.
Based on the above examples, one can very roughly approximate sensitivity relationships among potential future edm experiments. In table 1, we give current and anticipated edm bounds and sensitivities for nucleons, atoms and the deuteron. The last column provides a rough measure of their probing power relative to d_n.

Table 1. Current EDM limits in units of [e·cm], and long-term goals for the neutron, ^{199}Hg, ^{129}Xe, proton, and deuteron are given here. The neutron equivalent indicates the EDM value for the neutron to have the same physics reach as the indicated system.

Particle/Atom	Current EDM limit	Future Goal	~d_n equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg	$<3.1\times10^{-29}$	$\sim10^{-29}$	10^{-26}
^{129}Xe	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Proton	$<7.9\times10^{-25}$	$\sim10^{-29}$	10^{-29}
Deuteron		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}

3) Dimensional Analysis

To roughly estimate the scale of "new physics" probed by EDM experiments, we often assume on dimensional grounds

$$d_i \approx \frac{m_i}{\Lambda^2} e \sin\phi, \tag{18}$$

where m_i is the quark or lepton mass, $\sin\phi$ is the result of CP-violating phases, and Λ is the "new physics" scale. For m_q~10 MeV and $\sin\phi$ of order ½, one finds

$$\left|d_p\right| \sim \left|d_D\right| \sim 10^{-22} \left(\frac{1\text{TeV}}{\Lambda}\right)^2 \text{e}\cdot\text{cm}. \tag{19}$$

So d_p and d_D ~10^{-29}e·cm sensitivity probe Λ~3000 TeV. More realistically, the d_i generally results from a quantum loop effect and there is a further $g^2/16\pi^2$~1/100 suppression. So, for example, in supersymmetry one might expect

$$\left|d_p\right| \sim \left|d_D\right| \sim 10^{-24} \left(\frac{1\text{TeV}}{M_{\text{SUSY}}}\right)^2 \sin\phi \;\; \text{e}\cdot\text{cm}. \tag{20}$$

In such a theory, with $M_{\text{SUSY}} \leq 1$ TeV, $\sin\phi$ would have to be very small, $\leq 10^{-5}$ if a d_p or $d_D \geq 10^{-29}$e·cm were not observed. Of course, one hopes that the LHC may actually observe squarks in the TeV or lower range and that $\sin\phi \geq 10^{-5}$. If that is the case d_p and d_D will provide precise EDM measurements that will unveil their CP-violating nature and perhaps help to explain the matter-antimatter asymmetry of our universe.

Other new models of CP-violation from Left-Right symmetric gauge theories, additional Higgs scalars, etc. can also be studied using EDM experiments. In such cases d_p and d_D at 10^{-28}e·cm is competitive with or better than other EDM measurements, while at 10^{-29} e·cm they become our best hope for finding new sources of CP-violation. Couple that sensitivity with the relative theoretical simplicity of the proton and deuteron and it becomes clear that they hold great discovery potential. The storage ring method should therefore be vigorously pursued.

References:

1. J.H. Smith, E.M. Purcel, and N.F. Ramsey, Phys. Rev. **108**, 120 (1957).
2. I.B. Khriplovich, R.A. Korkin, Nucl. Phys. A **665**, 365 (2000), nucl-th/9904081; C.P. Liu and R.G.E. Timmermans, Phys. Rev. C **70**, 055501 (2004); M. Pospelov and A. Ritz, Ann. Phys. **318**, 119 (2005), hep-ph/0504231; O. Lebedev *et al.*, Phys. Rev. D **70**, 016003 (2004).