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Status of electric dipole moment (EDM) searches

B. W. Filippone[*1]
Kellogg Radiation Laboratory
California Institute of Technology
Pasadena, CA, USA
E-mail: bradf@caltech.edu

Motivated by the potential reach to high mass scales, many new searches for CP-violating electric dipole moments (EDM) of leptons, nucleons, atoms and molecules are underway. In many cases novel techniques are being applied to greatly increase the sensitivity to new physics (NP). The importance of improved searches in complimentary systems and the potential sensitivities of these new searches are discussed.

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1. Introduction

Because electric dipole moments (EDM) are predicted to be so small in the Standard Model (SM) their sensitivity to new physics is dramatic, reaching to mass scales of multi-TeV [1] and in some models up to PeV [2-4]. Present experimental limits on the neutron [5] and electron [6] EDM are approximately 6 and 10 orders of magnitude larger than the SM predictions [7-8] respectively. With this significant discovery potential, a large number of experimental searches are underway worldwide.

EDM expeirments have been underway for more than 60 years, motivated by their unique senstitvity to new sources of CP violation. Such CP violation, beyond that present in the Cabbibo-Kobayashi-Maskawa quark weak mixing matrix, could signal the presence of new physics while also providing a resolution to the puzzle of the matter-antimatter asymmetry of the universe as suggested many years ago by Sakharov [9].

2. Complementarity of EDM probes

In order to characterize the possible sources of particle EDMs, effective Lagrangians are usually constructed to include both the short distance (e.g. fermion EDMs) and longer distance sources (e.g. hadronic contributions parametrized via pion exchange) of CP-violation. These are often discussed in terms of a number of parameters such as:

- d_q, d_l - the elementary fermion EDMs for the quarks and leptons
- $\tilde{d}_q$ - the so-called quark chromo-electric EDMs that include gluonic interactions
- θ_{QCD} - the phase associated with the $G^{\mu\nu}\tilde{G}_{\mu\nu}$ term in the QCD Lagrangian
- Other CP-violating e-N and 3-gluon parameters

To access these possible sources of CP-violation a number of probes and techniques is required. At present there are not enough observables to completely constrain these parameters (see eg. [10-11]).

3. Present status of EDM searches

Among the EDM searches with the greatest the published sensitivity, three of them provide the most competitive constraints on new physics. These are the neutron, ^{199}Hg and ThO polar molecule EDM experiments. Each of these has recently provided new results. The neutron has a unique sensitivity to the quark EDM d_q and θ_{QCD}, while ^{199}Hg is primarily sensitive to the chromo-EDM $\tilde{d}_q$ and ThO to the electron EDM. The quark EDM sensitivity for ^{199}Hg results because it is a diamagnetic atom with the electron spins paired to up, greatly reducing sensitivity to the electron EDM. In contrast ThO is a polar molecule that can be optically pumped into a state that is highly sensitive to the electron EDM.

For the neutron, the Institut Laue-Langevin (ILL) experiment has used a more detailed analysis and improved calculations of systematic uncertainties as well as new data on internal field gradients to produce a new limit [5]:

$$|d_n| < 3.0 \times 10^{-26} \text{ e-cm (90\% confidence limit)}$$

This value is slightly larger than their previously published limit of 2.9 x 10^{-26} e-cm [12].

The ^{199}Hg experiment, using an improved apparatus, has recently published [13] an improved limit of

$$|d_{Hg}| < 7.4 \times 10^{-30} \text{ e-cm (95\% confidence limit)}$$

which is a factor of 4 more sensitive than their previous result [14].

A new experiment by the ACME collaboration [6] has improved the limit on the electron EDM using the polar molecule ThO. In this experiment a cold beam of ThO is prepared via lasers in a number of initial states, passes through a region of uniform electric and magnetic fields and is then measured via laser beams and photodetectors to search for the electric-field-dependent frequency shift of the spin precession in the magnetic field. A schematic of the apparatus (taken from their paper) is shown in Fig. 1. A particularly unique handle in this experiment is the ability to reverse the effective electric field seen by the electron, by flipping the orientation of the polar molecule, while keeping the direction of the electron spin and the applied electric and magnetic field fixed (see Fig. 1). This allows precise studies of systematic effects associated with changing the external electric field. The published limit from ACME is

$$|d_e| < 8.7 \times 10^{-29} \text{ e-cm (90\% confidence limit)}$$

This is a factor of ten improvement over the previous best limits [15-16].

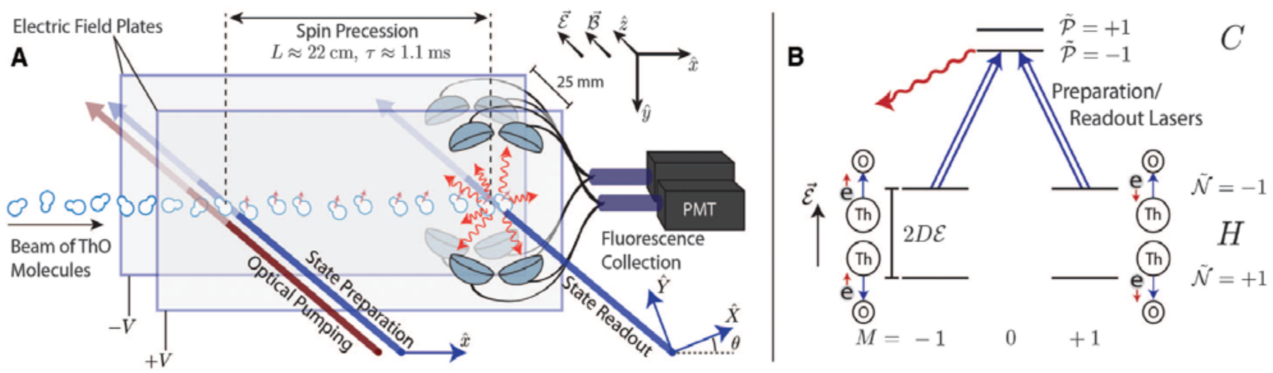

Figure 1: A. Schematic of the ACME apparatus for measuring the electron EDM. The beam of ThO is prepared and read out with lasers to measure the electric-field-dependent frequency shift that is characteristic of an EDM. **B.** Summary of state preparation of the ThO. The level diagram on the left shows the two states that can be selected where the effective electric field is flipped while the applied electric field is held fixed. Figure from ref [6].

While many other systems have been studied, their sensitivity to new physics is usually less than those discussed above, although this is a model-dependent statement. We will discuss many of these additional systems in the next section.

4. Future EDM sensitivity

A very active experimental program is underway to both improve the sensitivity of existing EDM searches and to explore additional systems.

For paramagnetic atoms and polar molecules, which are primarily sensitive to the electron EDM and the CP-violating e-N coupling, improvements in both the YbF [16] and ThO [6] experiments could eventually increase their sensitivity by a factor of 10. There is also the potential to trap ThO molecules allowing a longer measurement time compared to the cold molecular beam with a potential factor of 100 improvement [17]. New experiments using Cs, which has a different sensitivity to the effective theory parameters than the polar molecules, could reach sensitivities 10 – 50 times better than the published ThO limit using a Cs atomic fountain [18] or Cs confined in an optical lattice [19] .

New high sensitivity results from diamagnetic atoms are anticipated especially for highly-deformed, heavy, radioactive atoms. The high deformation and high proton number of these nuclei provide enhancement factors > 1000 in some cases. Programs are under development for ^{211}Fr [20] and ^{222}Rn/^{223}Rn [21], while a first result has been reported for ^{225}Ra [22] with a potential sensitivity of a factor of 100 better than the existing limit for ^{199}Hg.

For charged particles there is the extra challenge of confining the particles in the presence of an electric field. The muon EDM has been studied parasitically in magnetic storage rings nominally used to measure (g-2) for the muon. An improved value for the muon EDM is expected from the latest (g-2) running at Fermilab [23]. An electrostatic storage ring is also being discussed [24] for measuring the proton EDM with statistical sensitivity that could be 1000 time better than the present neutron sensitivity. For the electron EDM a group at JILA is developing an ion trap for HfF^+ [25] with potential sensitivity of a factor of 10 better than the present ThO limit.

The EDM of the tau can be accessed in e^+-e^- colliders via $e^+ + e^- \rightarrow \tau^+ + \tau^-$ by measuring the final state decay distributions. The published limit from Belle [26] will likely be improved in the near future using new data from both Belle and BaBar [27].

Recent developments in producing new sources of higher density trapped neutrons (so-called ultra-cold neutrons) have led to the development of a large number of new experiments at existing facilities. These experiments are summarized in Table 1. Of these new experiments, most use trapped ultra-cold neutrons as do all of the high sensitivity searches – i.e. those with sensitivity < 5 x 10^{-28} e-cm which is nearly a factor of 100 improvement over the existing limit. These higher sensitivity experiments are generally performed with measurement cells at room temperature and in vacuum using the techniques of the best published limit. This is not the case for one of the new techniques – the SNS nEDM experiment – which we will briefly discuss here.

The concept for the SNS nEDM experiment, as first discussed in ref. [28], is to use superfluid ^{4}He as both the neutron moderator and the measurement medium. The moderation is done using a beam of cold neutrons scattering from the phonons in the superfluid to produce a relatively high density of trapped ultra-cold neutrons. In addition, by using the liquid ^{4}He as an insulating dielectric much higher electric fields (by a factor of 5-8) can, in principle, be attained.

Experiment	**UCN source**	**Cell**	**Measurement Techniques**	**σ_d Goal (10^{-28} e-cm)**
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vacuum	Ramsey technique with E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vacuum	Ramsey for w, external Cs & ^{3}He, Hg co-magnetometer & Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vacuum	Room Temp. , Hg Co-mag., also external Cs magnetome-ter	< 5
RCNP/TRI-UMF	Superfluid ^{4}He	Vacuum	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 50 < 5
SNS nEDM	Superfluid ^{4}He	Liquid ^{4}He	Cryo-HV, ^{3}He capture for w, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vacuum	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 10?
LANL	Solid D_2	Vacuum	Ramsey technique with Hg	~ 30

Table 1: Summary of the ongoing searches for a neutron EDM. The third colum refers to the medium used in measuring the EDM, the fourth column refers to the measurement technique and the last column is the potential EDM sensitivity after several years of running.

Co-magnetometry, where a separate species cohabitating the neutron storage volume is used to correct for local magnetic field fluctuations, is performed with a small density of polarized ^{3}He that is added to the liquid ^{4}He. Because of the electron cloud around the ^{3}He atom, any contribution from the EDM of the ^{3}He nucleus is dramatically suppressed, allowing it to be used to monitor variations of the ambient magnetic field with SQUID magnetometers to measure the ^{3}He magnetization. In addition the polarized ^{3}He can be used as a neutron frequency monitor via the spin-dependent cross section for neutron capture by the ^{3}He which produces an energetic proton and triton that generates UV scintillation in the liquid He which can be down-converted to visible light and detected with photodetectors. A schematic of this apparatus is shown in Fig. 2 and is described in ref. [29]. The collaboration is presently completing R&D on the most challenging components and anticipates beginning integration of the components and conventional construction in less than 2 years. It is expected that new results for the neutron EDM will be forthcoming in the next several years from a number of the experiments listed in Table 1, with the full factor of 100 improvement in sensitivity obtained at least 5 years from now.

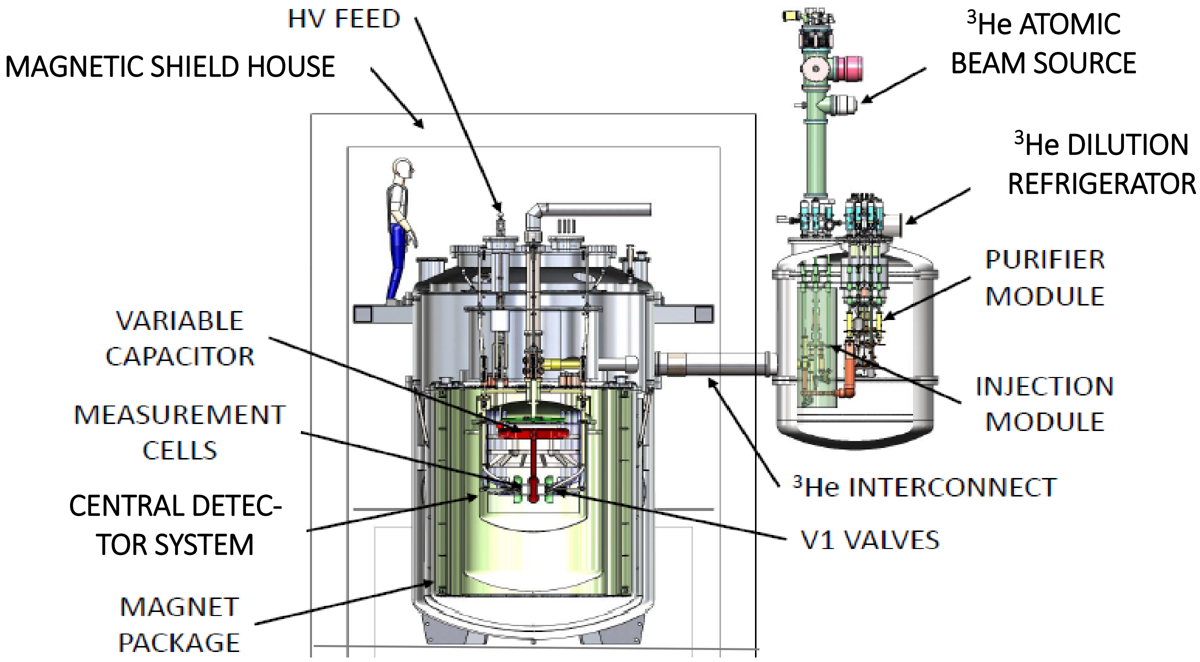

Figure 2: Schematic of the nEDM apparatus for measuring the neutron EDM at the Spallation Neutron Source at Oak Ridge National Laboratory.

5. Summary

Searches for EDMs continue to provide severe constraints on new sources of CP-violation in physics beyond the Standard Model. Present limits can provide constraints on only a subset of possible sources of EDMs in effective theories. Future highly sensitive searches in new systems and greatly improved searches in existing systems would allow an improved determination of the parameters in the effective theory and potentially discover a new source of CP-violation. A number of novel technologies are being brought to bear to improve the sensitivity to new physics from one to three orders-of-magnitude depending on the system.

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