The hunt for permanent electric dipole moments

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Abstract. The search for permanent electric dipole moments in non-degenerate systems has become a very active field of research in recent years. The experimental sensitivity has reached limits to probe physics beyond the Standard Model with high accuracy. This talk will review and summarize some of the ongoing efforts.

1. Introduction
The possible existence of permanent electric dipole moments (EDM) in nucleons, atoms, molecules, or other fundamental particles has motivated experimental physicists to push the limits of low energy precision studies for more than five decades. A non-zero EDM simply implies that electric charge is not uniformly distributed "inside" such a particle, giving rise to the violation of time-reversal(T) symmetry. Already in 1950 E. M. Purcell and N. F. Ramsey argued that a non-zero EDM could arise due to parity violation [1]. It is easy to comprehend this argument by studying the interaction Hamiltonian between external magnetic and electric fields and a particle with spin $s$:

$$H = -(\mu \cdot B + d \cdot E) = -(d_M \frac{s}{|s|} \cdot B + d_E \frac{s}{|s|} \cdot E).$$

(1)

Here $\mu$ and $d$ denote the magnetic and electric dipole moments of the particle. It is worth emphasizing that the direction of $\mu$ as well as $d$ has to be along the particle’s spin axis. While the magnetic field is even under parity transformation, the electric field is not, so a finite value of $|d|$ (or $d_E$) implies that $H$ does not conserve parity. In more recent years the concept of parity violation was expanded to the “CPT Theorem”. It is believed, even beyond the Standard Model of particle physics, that nature is invariant under a combined symmetry operation consisting of charge conjugation (C) and parity transformation (P) and time reversal (T). Indeed, the Hamiltonian in Eq. 1 does violate time reversal, and hence CP symmetry, if $|d| \neq 0$. In our discussion, we assume that no degenerate states exist in the system of interest.

The discovery of a finite EDM at present experimental sensitivities would unambiguously yield physics beyond the Standard Model (SM) of particle physics. Some recent experimental results, together with (CKM) Standard Model predictions are listed in table 1. Unless new physics increases the values of EDMs by orders of magnitude, present and near future experimental techniques will not suffice to test the SM predictions.
Table 1. Recent experimental limits on permanent EDMs (no claim of completeness is made).

| Particle | Limit [e cm] (≥ 90% C.L.) | Experiment | SM Prediction [e cm] |
|----------|---------------------------|------------|---------------------|
| $e^{-}$  | $10.5 \times 10^{-28}$    | Hinds et al. [2] | $< 10^{-38}$ [3] |
| $\mu$    | $1.8 \times 10^{-19}$     | Bennett et al. [4] | $< 10^{-36}$ [5] |
| $n$      | $2.9 \times 10^{-26}$     | Baker et al. [6]  | $< 10^{-32}$ [7] |
| $^{199}\text{Hg}$ | $3.1 \times 10^{-29}$ | Griffith et al. [8] | $\sim 10^{-33}$ [9] |
| $^{129}\text{Xe}$ | $3.4 \times 10^{-27}$ | Rosenberry et al. [10] | $\sim 10^{-34}$ [11] |
| $^{205}\text{Tl}$ | $9.4 \times 10^{-25}$ | Regan et al. [12] | |

The existence of a permanent EDM has numerous and far reaching implications, e.g. it could, at least partially, explain the baryon – anti-baryon asymmetry universe and it would reveal new sources of CP violation.

Section 2 describes some ongoing experimental efforts on neutron EDM searches with a focus on an experiment that will take place at the newly build Spallation Neutron Source (SNS, Oak Ridge National Laboratory (ORNL)). Section 3 summarizes briefly efforts on atomic and molecular systems.

2. Neutron EDM searches

The first neutron EDM measurement dates back to 1957 when J. H. Smith, E. M. Purcell, and N. F. Ramsey published their result of an experiment that was performed at ORNL using a magnetic resonance technique [13]. An upper bound of $(0.1 \pm 2.4) \times 10^{-20}$ e·cm was reported for the magnitude of the EDM. This was just the beginning of still ongoing efforts to find violation of fundamental time-reversal symmetry. During the past fifty years the limit was improved continuously at a rate of roughly one order of magnitude per decade. Basically all neutron EDM searches utilized magnetic resonance techniques and, since about 1980, the use of ultra-cold neutrons (UCNs) has become favorable over thermal or cold neutron beams. The kinetic energy of UCNs is so low that they can be easily trapped in containers (assuming coatings with large repulsive Fermi-potentials are applied), strong magnetic fields, or even gravitationally. The best limit on a neutron EDM was recently achieved at the ILL in Grenoble using polarized UCNs stored in a cylindrical trap. [6]. Figure 1 shows the basic components of the ILL experimental setup. The experimental procedure can be summarized as follows: First, longitudinally polarized UCNs were injected for about 20 s into a 21 l volume (trap). Inside the trap the neutrons were exposed to a combination of a weak uniform static magnetic field ($\approx 10$ mGauss) and an electric field with a magnitude of 10 kV/cm. The electric and magnetic field were aligned either parallel or anti-parallel to each other. After filling of the trap, an oscillating magnetic field acted on the neutrons for a short time interval ($\Delta T \approx 2$ s) rotating the spins perpendicular to the static fields. The frequency of these fields was close to the neutron Larmor frequency. A free spin precession followed for about 130 s. Then a second pulse was applied to rotate the neutron spins back to their original directions. Finally, the neutron polarization was measured to determine whether the electric field influenced the precession frequency. This technique is known as the Ramsey separated-oscillatory-field magnetic resonance method. Figure 2 shows a typical Ramsey fringe pattern. The final result reported by the collaboration constrains $d_n$ to less than $2.9 \times 10^{-26}$ e·cm [6].

The goal of upcoming neutron EDM experiments is to improve the present limit by a factor of about 100. Although the Standard Model of particle physics predicts only a value of $10^{-32} - 10^{-31}$ e·cm for $d_n$, an improvement of the present bound by two orders of magnitude could have interesting consequences. For example, the masses of new elementary (SUSY) particles...
necessary to generate such a sizable neutron EDM are comparable to energies accessible at the LHC assuming that the CP violating phases are of $O(1)$ [14]. Therefore, the discovery potential of SUSY particles at the LHC could be closely related to the discovery of a permanent EDM. Three parallel efforts have emerged. One experiment is presently constructed at the PSI in Switzerland [15], a second one will take place at the ILL in France [16], and finally the SNS-EDM experiment in the US [17]. All three experiments aim for comparable sensitivity. The following section describes the basic concept of the SNS-EDM experiment.

2.1. The SNS experiment

Inspection of the interaction Hamiltonian, Eq. 1, suggests that $d_n$ can be extracted by monitoring the change in spin precession frequency of the neutron when the electric field, $E$, is reversed relative to the magnetic field, $B$. Solving Eq. 1 for $d_n$ yields:

$$d_n = \frac{\hbar \Delta \nu}{4E} ,$$

where $\hbar$ is the Planck constant, $\Delta \nu$ is the change in precession frequency when $E$ is reversed relative to $B$, and $E$ is the magnitude of the electric field. The statistical uncertainty on $\delta d_n$ is bounded by the uncertainty principle:

$$\delta d_n = \frac{\hbar}{4ET_m \sqrt{mN}} ,$$

where $T_m$ is the time to perform a neutron spin precession measurement, and $m$ denotes the number of separate complete measurements with $N$ neutrons. It is obvious from this formula that long neutron spin precession times, many measurement cycles, and a large number of neutrons are needed to achieve a minimum statistical uncertainty.

Figure 1. The Sussex-RAL-ILL EDM apparatus.

Figure 2. A typical Ramsey resonance curve for spin-up neutrons.
The newly constructed SNS at the Oak Ridge National Laboratory commenced operation in 2006 and appears to be an ideal environment to conduct a high precision neutron EDM experiment. A 1.4 MW pulsed proton beam ($E_p = 1.0$ GeV) impinges on a high power mercury target and spallation neutrons are generated with unprecedented (pulsed) intensity. After moderation the neutrons have a typical temperature of $T_n \sim 20$ K. In 1975, R. Golub and R. Pendlebury pointed out that the local density of free neutrons can be increased significantly when they are converted to ultra-cold neutrons (UCNs) [18]. Specifically, neutrons with a wavelength of 8.9 Å can be down-scattered to milli-Kelvin temperatures via single-phonon excitations in superfluid helium-4 [19]. We plan to exploit this concept with the goal to capture and store such UCNs in a container.

The SNS cold neutron beam will be used in combination with a system of velocity filters (choppers) to select neutrons with a wavelength around 8.9 Å. These neutrons will then be transported and polarized using standard neutron super-mirror techniques, and finally they will be injected into two target cells containing superfluid helium-4. Any neutron that experiences a conversion to a UCN will have a chance to be trapped. As in other EDM searches, the effect of a (strong) electric field (up to 50 kV/cm) on the precession frequency of the neutrons will serve as an indication of a non-zero EDM. In addition to the electric field a very uniform small magnetic field ($O(10 \text{ mG})$) will serve as a quantization axis. The main challenge of the experiment is to measure the precession frequency of the neutrons very precisely. To accomplish this goal we plan to take advantage of the strong spin dependence in the reaction: \[ \bar{n} + ^3\text{He}^{++} \rightarrow t + p + 764 \text{ keV}. \] For that purpose, a small amount of polarized $^3$He will be injected into the helium-4 cell as well. Both the neutrons and $^3$He nuclei will be prepared in such a way that all spins are aligned along the same direction (perpendicular to the magnetic field) at the beginning of a measurement cycle. Due to the difference in the magnetic moments of the two species, their spins will precess at different rates and therefore the rate at which the above reaction occurs is modulated accordingly. The protons released in this process carry enough energy to generate scintillation light in the superfluid medium. We plan to detect this scintillation light and use it as a measure of the relative spin precession frequency. A non-zero neutron EDM will manifest itself in a correlation between the light modulation and the direction of the electric field. Note that the effect of an external electric field on the precession of the helium-3 spins is vastly reduced due to the shielding effect of the atomic electrons. We also intend to monitor the precession frequency of the $^3$He spins independently (using SQUIDs). This frequency information will help to keep track of the stability of the magnetic field.

The experimental techniques described in this paper appear to be promising to overcome statistical limitations experienced in previous EDM searches. Given a realistic funding scenario data taking is expected to start around 2017. A more complete description of the whole experiment can be found in Ref. [20].

3. EDM searches in atomic and molecular systems

The apparent sensitivity to physics beyond the Standard Model has revived a large number of EDM searches on atomic systems in recent years. Current searches of time-reversal violation in atomic systems can be split into two categories: highly polar diatomic (paramagnetic) molecular systems and diamagnetic atoms with, ideally, highly deformed nuclei. Polar molecules with unpaired electrons exhibit an increased sensitivity to the electron EDM since the bound electron is preferentially located along the internuclear axis and internal electric fields can reach tens of gigavolts per centimeter. In addition, relatively low external electric fields are needed (of order 10 kV/cm or less) to align such molecules. However, the main challenge with polar molecules is finding an efficient way to generate large quantities with low rotational states since only molecules with sufficiently low values of angular momentum have a detectable sensitivity to EDMs ($E \cdot d_{\text{mol}} > E_{\text{rot}}$). Systems like HfH$^+$, PbF, PbO, ThO, WC, and YbF are studied as
possible candidates. Hinds and collaborators published recently a new result on $d_e$ using YbF. Their measurement yielded a value consistent with zero and an upper limit of $10.5 \times 10^{-28} \text{e-cm}$ was reported [2].

Diamagnetic atoms, on the other hand, reveal a higher sensitivity to nuclear EDMs. Especially atoms that can be easily spin-polarized are excellent candidates for atomic EDM searches. The most precise limit on a diatomic atom thus far has been reached at the University of Washington (Seattle). Using optically pumped $^{199}$Hg in a multi-cell configuration it was found that $d_{199\text{Hg}} < 3.1 \times 10^{-29} \text{e-cm}$ [8]. This result by itself puts severe constraints on many supersymmetry inspired models. It turns out that $^{225}$Ra has emerged as a very promising candidate for EDM searches. This radium isotope possesses a large Schiff moment which increases the sensitivity to T-violating effects significantly. Due to its large octupole deformation, the Schiff moment predicted for $^{225}$Ra [21] is expected to yield an enhancement factor somewhere between 100 and 1000 over $^{199}$Hg. Two groups at Argonne National Lab (ANL) [22] and at KVI (Groningen) [23] are in the process of developing an EDM experiment using the $I = 1/2$ radium isotope. Although $^{225}$Ra is radioactive, its half life of 14.9 days is sufficiently long to be useful for EDM studies. The ANL group has already demonstrated the trapping of laser cooled Ra atoms in a magneto-optical trap (MOT) as well as successful transfer to a far off resonant optical

**Figure 3.** Conceptual design of the SNS-EDM apparatus.
dipole trap (ODT) - two essential steps in performing the measurement. The plan is to transport about $10^4$ atoms into a region of uniform electric and magnetic fields by means of a mobile ODT. Within a small volume of about $4 \times 10^{-3} \text{ mm}^3$ the atoms will be polarized by optical pumping. As described above the existence of a non-zero EDM will be probed by monitoring the spin precession as a function of the electric field direction. Compared to other EDM searches this experiment has several systematic advantages; e.g. the small size of the sample volume simplifies the generation of uniform electric and magnetic fields; therefore, effects due to motional electric fields ($E = v \times B$) will be minimal. Further, electric fields of order 100 kV/cm can be produced relatively easily since the electrode separation is only about 2 mm. All components of the experiment appear to be working and first results can be expected within the next two or three years.

4. Summary
In recent years the hunt for permanent electric dipole moments has emerged as a very active field of research. Many groups around the world are in the process of developing new devices and setups in order to improve EDM limits on the electron, atoms, neutron, and other fundamental particles. Even new electrostatic particle storage rings are being considered to measure the EDM of the deuteron. Within the next decade several new results should emerge putting severe constraints on many new physics models.

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