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Electric dipole moments: Flavor-diagonal CP violation

Les moments dipolaires électriques : Violation de CP diagonale de saveur

Oscar Naviliat-Cuncic [a,*], Rob G.E. Timmermans [b]

[a] *NSCL and Department of Physics and Astronomy, Michigan State University, East-Lansing, MI 48824, USA*
[b] *KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*

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ABSTRACT

Searches for permanent electric dipole moments of particles, nuclei, atoms and molecules offer an extraordinary discovery potential to new mechanisms of CP violation beyond those incorporated in the standard electroweak model. The electric dipole moments induced by speculative scenarios, on different physical systems, require a complementary approach to pave the way to the fundamental CP-violating mechanisms. New avenues presently being explored in order to improve the experimental sensitivities include projects that consider the trapping of neutral particles, the confinement of charged particles in storage rings as well as the use of radioactive nuclei.

RÉSUMÉ

La recherche de moments dipolaires électriques de particules, noyaux, atomes et molecules offre un potentiel extraordinaire de découverte de nouveaux mécanismes de violation de CP autres que ceux inclus dans le modèle standard électrofaible. Les moments dipolaires électriques induits par des scénarios spéculatifs, sur divers systèmes physiques, exigent une approche complémentaire afin d'ouvrir la voie vers les mécanismes fondamentaux de violation de CP. Les nouveaux chantiers explorés actuellement afin d'améliorer les sensibilités expérimentales incluent des projets qui considèrent le piègeage de particules neutres, le confinement de particules chargées dans des anneaux de stockage ainsi que l'utilisation de noyaux radioactifs.

1. Introduction

Electric dipole moments (EDMs) of particles, nuclei, atoms and molecules play a privileged role in the search for new mechanisms of CP violation [1–6]. A permanent EDM violates both parity (P) and time-reversal (T) invariance. Because of rotational invariance, the EDM vector, $\boldsymbol{d}$, of a quantum-mechanical system in a pure state must be parallel (or anti-parallel) to its angular momentum, $\boldsymbol{S}$, i.e. $\boldsymbol{d} \propto \boldsymbol{S}$. Since $\boldsymbol{d}$ is an ordinary (polar) vector, it changes sign under P, while $\boldsymbol{S}$, an axial vector, does not. On the other hand, $\boldsymbol{S}$ changes sign under T, but $\boldsymbol{d}$ does not. Therefore, $\boldsymbol{d}$ has to vanish if P and T are exact symmetries. However, as emphasized by Purcell and Ramsey [7], the validity of such symmetry arguments must ultimately

* Corresponding author.
E-mail addresses: naviliat@nscl.msu.edu (O. Naviliat-Cuncic), timmermans@kvi.nl (R.G.E. Timmermans).

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rely on experiments. According to the celebrated CPT theorem, any local, Lorentz-invariant quantum field theory is also invariant under the combined operations of charge conjugation (C), P and T; hence T violation is equivalent to CP violation.

In the electroweak sector of the Standard Model (SM), CP violation is parametrized by one complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix, which accounts for the CP-violating effects observed in the K and B meson systems. For a flavor-diagonal quantity like the EDM, non-zero values can, however, only arise at higher order (at least three loops), because all three quark families have to be involved. For the systems considered so far, the SM predictions of EDM values are too small to be detected in the foreseeable future. The measurement of a non-zero EDM would therefore have extremely important implications, as an unambiguous signal of a new source of CP violation. In contrast, in many extensions of the SM, like supersymmetry [8], or left–right symmetric models [9], non-zero EDMs occur naturally at one-loop level. Such new interactions, involving particles with masses of the order of a few TeV, could be revealed in the new round of experiments for searches of particle and atomic EDMs.

In the strong sector of the SM (QCD), CP violation is possible because of a non-perturbative, topological boundary term, parametrized by the QCD "vacuum angle" $\bar{\theta}$. The limit on the neutron EDM obtained 30 years ago, implied already then that the value of $\bar{\theta}$ is tuned to zero to less than 1 part in 10^9 [10]. This so-called strong CP problem, arising from such an unnaturally small value of $\bar{\theta}$, could be solved by a spontaneously broken symmetry. However, the required Goldstone boson, the axion, a credible candidate for dark matter, has so far eluded detection.

The search for new sources of CP violation is also strongly motivated by cosmology and, in particular, by the observed non-vanishing matter–antimatter asymmetry of the Universe. According to a profound idea of Sakharov [11], the particle physics of the evolving Universe in its very early stages has to involve interactions that contain CP violation (together with baryon-number violation and a departure from thermal equilibrium) in order to produce this asymmetry. It is generally accepted, however, that the two known sources of CP violation in the SM, the CKM phase and the $\bar{\theta}$-term, are not sufficient to account for the observed asymmetry, so that new sources of CP violation are expected to exist.

Over the years, many experiments have searched for non-zero EDMs [2,6] with ever increased precision. In particular, the limit on the neutron EDM has been improved spectacularly over 50 years [5,12]. Limits on EDMs of charged particles, such as the electron and the proton, have so far been derived from experiments with selected neutral atoms or molecules. The most stringent limit for an EDM has been obtained for the ^{199}Hg atom [13]. In such a diamagnetic atom, with paired electron spins in a closed-shell, the EDM of the system arises mainly from the EDM of unpaired nucleons and from T-violating interactions within the nucleus. The precision on the electron EDM as obtained in an experiment with paramagnetic ^{205}Tl atoms [14] has recently been improved with a technique using the dipolar molecule YbF [15]. In experiments with neutral atoms, the EDM signal is severely suppressed due to the screening of the applied external electric field by the atomic electrons, a famous general result known in the EDM literature as Schiff's theorem [16,17]. More recently, new highly sensitive methods have been proposed to measure directly the EDMs of charged particles, such as the muon, the proton, the deuteron or light ions, in storage rings [6].

In this article, we review the theoretical and experimental status of the EDM searches, emphasizing the state-of-the-art of the field and recent developments.

2. Theoretical considerations

Theoretical research indicates that there is, in general, no sound reason to favor a specific system in the search for a non-zero EDM. The measurement of either a non-zero value of $\bar{\theta}$ or of CP violation beyond the SM will be ground-breaking discoveries. In case a non-zero EDM is observed, a number of EDM experiments on different systems will be required, together with complementary results from future collider searches and other high-precision electroweak studies, in order to identify the nature of the underlying, microscopic CP violation. The role of theory in this road-map is illustrated with the scheme shown in Fig. 1. The experiments on various systems all connect to the fundamental theory of CP violation to be uncovered. Many theory papers consider a "top–down" approach, starting from particular SM extensions, such as SUSY [8,18], to work out predictions for EDMs. Complementary, "bottom-up" approaches investigate the sensitivity of the various experiments to the underlying theory. In both cases, hadronic (QCD), nuclear, and/or atomic theories are required to select the most promising systems for experiments, and to interpret the measurements in terms of fundamental T-odd quantities, such as the $\bar{\theta}$ term, quarks EDMs, quark and gluon color (chromo-)EDMs, etc.

Searches for EDMs of para- or diamagnetic atoms (or molecules) have traditionally played a key role. Theoretically, the interpretation of an atomic EDM is complicated because of the interplay of (many-body) atomic, nuclear, and hadronic physics. Moreover, Schiff's theorem implies that the EDM of the nucleus in a neutral diamagnetic atom is not detectable, apart from small corrections. Classically, Schiff's theorem can be understood as a screening effect. An atomic EDM is probed by placing the atom in a combination of external magnetic and electric fields. If the atom has a finite EDM, its interaction with the external electric field leads to a shift in the precession frequency of its spin that depends linearly on the external field. However, a neutral system cannot accelerate in an external electric field. This implies that the constituents of the atom, the point-like electrons and the nucleus, will rearrange and screen out the effect of the external field at the location of each of the charged constituents. If the electrons or the nucleus possess a non-zero EDM, changes in the interaction energy will be exactly canceled by the internal fields induced by atomic polarization. Hence, for point-like, non-relativistic constituents interacting with electrostatic (Coulomb) forces, there will be no effective atomic EDM.

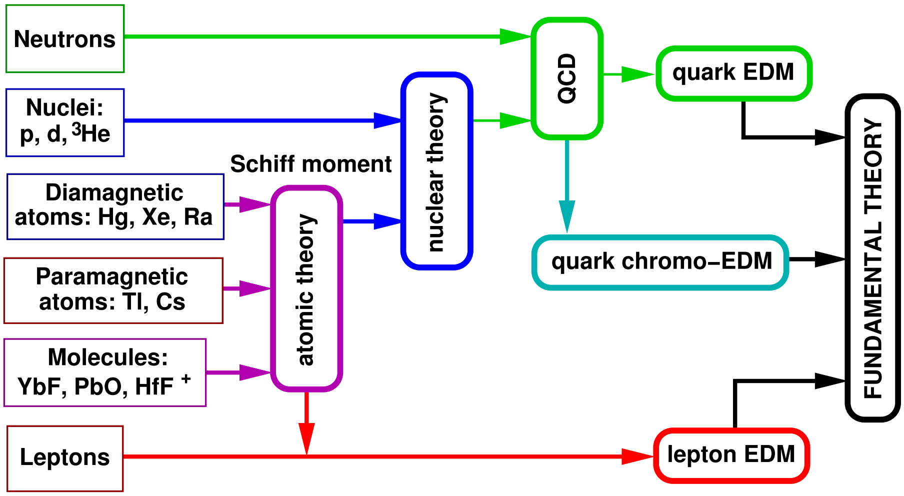

Fig. 1. Schematic view of the connection between the results from experiments in various systems (left boxes) and the fundamental microscopic CP violation to be discovered (right box). The role of hadronic (QCD), nuclear, and atomic theory in making predictions and in interpreting the measurements is indicated by the arrows and the boxes in between.

Schiff himself already pointed out [16] that there are corrections to exact screening (so-called "loopholes") that arise if any of the constituents with an EDM either has relativistic speed, a finite size, or non-electrostatic interactions. Finally, T-odd interactions between the constituents result in an atomic EDM that evades the Schiff screening. Because of these corrections and of the exquisite sensitivity of the measurements, atomic EDM experiments place important constraints on the electron EDM and on T-odd nuclear forces. The present limits on the electron EDM are derived from heavy paramagnetic atoms and from dipolar molecules, where the Schiff theorem is evaded mainly by the relativistic speed of atomic electrons (and by T-odd electron–nucleon forces). The general features of the Schiff screening and its corrections were identified by Schiff and subsequently discussed in other works (see e.g. Refs. [19–21]). The intricacies of implementing the Schiff screening and the various loopholes are detailed in Ref. [22].

An amplification of the electron EDM [17] occurs, in fact, in heavy paramagnetic atoms and polar molecules. The EDM of the atom is given by

$$d_{\text{atom}} = \sum_{n'} \frac{\langle ns| - d_e(\beta - 1)\boldsymbol{\sigma} \cdot \boldsymbol{E}|n'p\rangle\langle n'p| - e\boldsymbol{r}|ns\rangle}{E_{ns} - E_{n'p}} + c.c. \tag{1}$$

where β is the Dirac matrix and $-e\boldsymbol{r}$ the dipole operator. The enhancement factor scales as $d_{para}/d_e \simeq Z^3\alpha^2$, where a factor $Z^2\alpha^2$ is due to relativity and an additional factor Z comes from the field of the nucleus. For typical external fields of size $E_{ext} \simeq 10^{1-4}$ V/m, the internal field is no less than $E_{int} \simeq 10^{8-10}$ V/m. An additional enhancement results if there are accidental near-degeneracies between the s and p atomic levels. Realistic atomic calculations predict, for instance, $d_{para}/d_e \simeq$ 100, -535, 1150, and 40.000, for Cs, Tl, Fr, and Ra, respectively. For a polar molecule, the almost ion-like charge separation results in a huge enhancement factor that essentially cancels the Schiff screening.

For diamagnetic atoms, non-zero effects come from the finite size of the nucleus that leads to imperfect shielding and from magnetic and other, higher-order, multipole interactions between the nucleus and the atomic electrons. The finite-size correction becomes more important in heavier atoms, where a residual T-odd interaction arises because the atomic electrons penetrate the nucleus. This produces an atomic EDM proportional to the so-called Schiff moment of the nucleus, often expressed as the offset of the nuclear charge and dipole distributions. The calculation of the Schiff moment involves a many-body nuclear model, and approximate expressions for it have been derived. These have been used in subsequent theoretical treatments of the EDMs of ^{199}Hg and other atoms, from which limits on CP-violating parameters have been obtained.

In order to illustrate the theoretical estimates of the various hadronic EDMs and their relations, let us consider a simplified P- and T-odd two-nucleon interaction mediated by pions. Since the EDM operator $e\boldsymbol{r}$ is long-range, one can naively assume that one-pion exchange dominates, and short-range terms involving heavy degrees of freedom are subleading (and more model dependent). In that case, there are three independent P- and T-odd interactions of isoscalar, isovector, and isotensor type, *viz.*

$$H_{int} = \overline{N}\big(\bar{g}_\pi^{(0)}\boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\big(3\tau_z\pi^0 - \boldsymbol{\tau} \cdot \boldsymbol{\pi}\big)\big)N \tag{2}$$

where the three T-violation parameters $\bar{g}_\pi^{(0,1,2)}$ are related to, for instance, the quark EDMs and the quark and gluon color EDMs (Fig. 1) by non-perturbative QCD. It is natural to assume that $\bar{g}_\pi^{(0,1,2)}$ arise from T-violation at the same scale and,

Table 1
Theoretical estimates of the sensitivity of some EDM in terms of CP-odd pion–nucleon coupling constants (in e fm).

System	$\bar{g}^{(0)}$	$\bar{g}^{(1)}$	$\bar{g}^{(2)}$
n	0.14	0.00	−0.14
p	−0.05	0.03	0.14
D	0.09	0.23	0.00
^{129}Xe	6×10^{-5}	6×10^{-5}	12×10^{-5}
^{199}Hg	2×10^{-6}	2×10^{-4}	-3×10^{-5}
^{225}Ra	−0.06	−0.12	0.11

hence, they should be numerically of the same order of magnitude. By calculating the EDMs of various systems in terms of $\bar{g}_\pi^{(0,1,2)}$, their sensitivity can be quantified ("bottom-up"). Alternatively, $\bar{g}_\pi^{(0,1,2)}$ can be estimated in "top–down" models of CP violation.

The Schiff moment of ^{199}Hg in terms of T-odd pion couplings has been evaluated by two independent groups [23,24] in a many-body nuclear calculation, yielding respectively

$$\langle S_z \rangle_{\mathrm{Hg}} = 0.00 g_\pi \bar{g}_\pi^{(0)} + 0.06 g_\pi \bar{g}_\pi^{(1)} - 0.01 g_\pi \bar{g}_\pi^{(2)} \; e\,\mathrm{fm}^3 \tag{3}$$

$$\langle S_z \rangle_{\mathrm{Hg}} = 0.01 g_\pi \bar{g}_\pi^{(0)} + 0.07 g_\pi \bar{g}_\pi^{(1)} - 0.02 g_\pi \bar{g}_\pi^{(2)} \; e\,\mathrm{fm}^3 \tag{4}$$

where g_π is the ordinary pion–nucleon coupling constant. Core polarization is important and reduces the single-particle result [25]. The two calculations are in remarkable agreement. (A recent calculation [26] gives, however, a much smaller result for the isovector part.) The EDM of atomic radium is enhanced by a factor $\simeq 10^4$ from an accidental atomic degeneracy, and an additional factor results from sizable octupole deformation in the neutron-rich isotopes [27,28]. Dobaczewski and Engel [29] find for the Schiff moment of ^{225}Ra

$$\langle S_z \rangle_{\mathrm{Ra}} = -1.5 g_\pi \bar{g}_\pi^{(0)} + 6.0 g_\pi \bar{g}_\pi^{(1)} + 4.0 g_\pi \bar{g}_\pi^{(2)} \; e\,\mathrm{fm}^3 \tag{5}$$

The enhancement factors overcome the Schiff screening, compared to ^{199}Hg above.

An important question is how the EDMs of diamagnetic atoms compare to those of the neutron, the proton, and light nuclei, in particular the deuteron D [30,31] and ^{3}He [32]. The dominant contribution to the nucleon EDM is isovector and is given by a famous result [10] as

$$d_N \simeq -\frac{\tau_z g_\pi}{4\pi^2} \left(\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)} \right) \log(M/m_\pi)\, e/M \tag{6}$$

For several reasons, the deuteron is a very interesting candidate for an EDM measurement. It is the simplest case with a P- and T-odd NN interaction, and the nuclear physics is well under control. The EDM is the sum of the proton and neutron EDMs plus a "two-body" polarization contribution dominated by one-pion exchange, which admixes the opposite-parity P-wave into the deuteron ground state:

$$\boldsymbol{d}_D^{pol} = \left\langle {}^3S_1 \middle\| \tau_-^z e\boldsymbol{r} \middle\| {}^3P_1 \right\rangle / \sqrt{6} \tag{7}$$

In terms of the T-odd pion couplings, one finds numerically

$$d_n = 0.14 \left[\bar{g}_\pi^{(0)} - \bar{g}_\pi^{(2)} \right] e\,\mathrm{fm} \tag{8}$$

$$d_D = 0.09 \bar{g}_\pi^{(0)} + 0.23 \bar{g}_\pi^{(1)} \; e\,\mathrm{fm} \tag{9}$$

This demonstrates that the deuteron is in general complementary to the neutron. With QCD sum rules, one can express the pion couplings in terms of quark chromo-EDMs. In this particular model one finds that the deuteron is more sensitive than the neutron, viz.

$$d_n = 0.49 d_u^c - 0.01 d_d^c \tag{10}$$

$$d_D = 5.22 d_u^c - 4.67 d_d^c \tag{11}$$

The spin-1 deuteron can also have a magnetic quadrupole (M2) moment, which is unscreened. Finally, $^3\mathrm{He} \simeq {}^4\mathrm{He} + n_{hole}$, so that for the one-body contributions one expects $d_{^3\mathrm{He}} \simeq d_n$. The two-body contributions, d^{pol}, are larger, however [32]. One concludes that the EDMs of n, D, and ^{3}He are linearly independent. The arguments can be made more model independent and precise by using the effective field theory that describes QCD at low energies: chiral perturbation theory [33–35].

Table 1 presents the theoretical estimates obtained in this simplified model, with CP-odd pion–nucleon coupling constants, and shows the sensitivities of some proposed light nuclei and diamagnetic atoms for future EDM experiments. In general, the analysis is more complicated. The stringent limit on the ^{199}Hg EDM [13] provides (model-dependent) limits on several sources of CP violation, including the electron, neutron, and proton EDMs and CP-odd electron–nucleus forces. A comprehensive discussion for diamagnetic atoms, for instance ^{129}Xe, ^{199}Hg, and ^{225}Ra can be found in Ref. [36].

Table 2
Present upper limits (at 95% C.L.) on the values of EDMs for several physical systems. The upper part lists EDMs directly obtained from experiments. The lower part presents those inferred from the indicated measurements.

System	Limit [e cm]	Technique	Reference
μ	1.8×10^{-19}	Tilt of μ^- and μ^+ spin precession planes in a storage ring	[37]
τ	4.5×10^{-17}	Triple correlation observables in $e^+e^- \to \tau^+\tau^-$	[38]
n	3.4×10^{-26}	Separated oscillating fields magnetic resonance with stored UCNs	[12]
Λ^0	1.5×10^{-16}	Spin precession in motional electric field	[39]
^{199}Hg	3.1×10^{-29}	Larmor precession frequency of atoms in vapor cells	[13]
^{205}Tl	1.2×10^{-24}	Separated oscillating fields magnetic resonance with atomic beam	[14]
e^-	1.4×10^{-27}	From EDM of dipolar molecule YbF	[15]
p	7.9×10^{-25}	From EDM of diamagnetic ^{199}Hg atom	[13]

3. Experimental results and future perspectives

The field of EDM measurements provides a marvelous example of the intellectual creativity in experiments using atomic and nuclear physics techniques at low energies. Since the EDM vector, $\boldsymbol{d}$, must be oriented along its angular momentum, the measurement of an EDM essentially consists in looking for a small change in the spin precession (frequency or direction) of the system, in the presence of magnetic and electric fields. The electric fields can be applied in different ways like using external electrodes, or be induced in the particle rest frame due to its motion in a magnetic field, or still be generated at the atomic scale in a crystal, where the intensities are several orders of magnitude larger than the fields directly produced in the laboratory.

One of the main difficulties in these measurements resides in the identification of spurious effects, which could mimic the signal of an EDM and need to be separated from a possibly true signature. When comparing the strengths of the electric dipole interaction, dE, with the magnetic dipole one, μB, the present limit reached for instance for the neutron (Table 2) corresponds, under typical experimental conditions for E, to a static magnetic field B of the order of 10^{-12} G. This, in turn, is to be confronted with the amplitude of magnetic field fluctuations in the environment of an urban laboratory, of about 10^{-2} G (in a typical frequency range), and shows the importance of magnetic shielding and control.

The most sensitive EDM measurements have been carried out in neutral systems (neutron, atoms, molecules), but several charged systems present complementary sensitivities to new mechanisms of CP violation. A charged particle at rest, or at very low energy, located in a strong electric field, would be accelerated by the Coulomb force and escape observation. This precluded, during a long time, direct EDM measurements to be carried out on charged particles, since a sensitive experiment requires a long interaction time of the particle with the electric field. The situation is different for fast particles moving in a magnetic storage ring. In the particle rest frame, the external magnetic field induces an intense radial electric field that would act on the EDM and possibly affect the spin precession. New dedicated experiments consider to exploit this effect for the measurement of charged particles EDMs.

3.1. Present limits

Searches for non-zero permanent EDMs have so far produced null results. The three most frequently measured systems are the neutron, paramagnetic atoms or molecules and diamagnetic atoms. The most stringent limits obtained so far are summarized in Table 2. The upper part presents the limits directly obtained from experiments and the lower part shows the limits for the electron and the proton as inferred from measurements in molecular and atomic systems. Details about the evolution of EDM searches as well as on experimental aspects can be found in recent reviews [2,5,6].

3.2. Current developments

The field of EDM searches has changed dramatically in the past few years, with a number of new proposals and plans for challenging measurements in a variety of systems other than the traditional neutron and atoms. We summarize here some of the recent developments.

3.2.1. Leptons

The limits on the electron EDM have traditionally been obtained from measurement in paramagnetic atoms or molecules and those are discussed below.

The present limit on the muon EDM (Table 2) was obtained at Brookhaven National Laboratory (BNL) [37], as a byproduct of the measurement of the muon anomalous magnetic moment in a storage ring. A new proposal at the Fermi National Accelerator Laboratory [40] considers the relocation of the BNL storage ring for a fourfold improvement on the muon anomalous magnetic moment. The proposal includes also a parasitic measurement of the muon EDM with a projected improvement in sensitivity by two orders of magnitudes below the current limit.

Dedicated experiments, with possibly higher sensitivities, have also been proposed. An attractive scheme for measurements of charged particles EDMs in storage rings is the so-called "Frozen Spin Method" [41]. In a proper configuration of the vertical magnetic field, the particle velocity, the particle anomalous magnetic moment and an externally radial electric field, the effect due to an EDM can be enhanced while reducing also the spin precession due to the magnetic moment. For longitudinally polarized muons, the EDM would manifest itself as a spin rotation out of the beam axis.

This concept has recently been discussed [42] for a measurement of the muon EDM at the level of 7×10^{-23} $e\,$cm in one year, using a compact (0.42 m radius) storage ring and 125 MeV/c muons. The goal seems feasible at existing muon facilities like the Paul Scherrer Institute (PSI) in Villigen, Switzerland. A project at the Japan Proton Accelerator Research Complex [43] considers improving the present limit on the muon EDM by about five orders of magnitude. The scheme is based on the storage of 500 MeV/c muons in a ring of 7 m radius.

3.2.2. The neutron

The first dedicated searches for a permanent EDM in a quantum system were carried out with neutrons [44]. The experimental sensitivity of the neutron EDM has improved by six orders of magnitude in about 50 years. The continuous technical refinements has culminated in the present limit (Table 2) obtained at the Institut Laue–Langevin (ILL) in Grenoble with ultra-cold neutrons (UCN) stored in a material bottle [12]. A crucial feature of this experiment was the use of an atomic mercury magnetometer cohabiting the UCN storage cell. Spin-polarized Hg atoms filled practically the same volume as the neutrons and the measurement of their spin precession enabled monitoring of the magnetic field variations. The precision on this result is mainly dominated by statistics, due to the UCNs densities available, of about 10 cm^{-3}, but systematic effects are not much far off.

A new experiment is being prepared [45] at the same ILL UCN source. The setup includes a recuperated double chamber apparatus used in previous measurements at the Petersburg Nuclear Physics Institute in Gatchina. The experiment operates essentially in the same way as earlier ones with a number of improvements in the infrastructure. A statistical sensitivity of 1.5×10^{-26} $e\,$cm is anticipated in 200 days of operation at ILL.

Significantly larger sensitivities are expected from experiments coupled to new UCN sources which use mechanisms for the UCN production that circumvent Liouville's theorem. The presently most advanced projects rely on the UCN production using either a 8.9 Å cold neutron beam incident on super-fluid ^{4}He, at ILL [46] and at the Spallation Neutron Source (SNS) in Oak Ridge [47], or a spallation target surrounded by a solid deuterium converter at PSI [48]. In the first two, the UCN sources are incorporated to the EDM apparatus and the measurements are to be performed under cryogenic conditions. For the solid deuterium source [49], the UCN are extracted in vacuum, at room temperature, towards the experiments where the anticipated densities are of about 10^3 UCN/cm^3. The combination of a Pb spallation target surrounded by a UCN converter volume containing super-fluid ^{4}He has also been demonstrated, at the Research Center for Nuclear Physics (RCNP) in Osaka, to be an efficient scheme for UCN production [50].

Besides the mode of UCN production and the fact that the applied electric fields in LHe should be significantly stronger than those used in vacuum, the two cryogenic experiments are conceptually very different. The CryoEDM experiment installed at ILL [46] will control the magnetic field with SQUID magnetometers located outside the UCN storage cells. The project expects to reach a sensitivity level of 10^{-27} $e\,$cm in a first phase and 10^{-28} $e\,$cm when moved to a new cold neutron beam line of higher intensity. The super-fluid ^{4}He setup to be installed at SNS [47] will incorporate many innovations and challenging techniques including spin-polarized ^{3}He serving both as co-magnetometer, filling the UCN storage cells, and as neutron detector, looking at the scintillation light from the capture reaction as a function of the Larmor precession frequency. This project aims at reaching a sensitivity below 10^{-28} $e\,$cm on a longer time scale [5].

The spectrometer used by the Sussex/Rutherford Appleton Laboratory/ILL collaboration, which yielded the present best limit on the neutron EDM [12], has been moved from ILL and it is presently installed at PSI. The spectrometer has been refurbished and modified at several places what improved its figure of merit [48]. The nEDM collaboration at PSI is currently starting taking data at the new spallation UCN source [49]. It is expected that the level of 5×10^{-27} $e\,$cm can be reached in two years of operation. In a second step, this collaboration aims at further improving the sensitivity by an order of magnitude, with a new EDM spectrometer presently under construction [48].

A new spallation UCN source using super-fluid ^{4}He and a new external EDM apparatus at room temperature are under construction at RCNP. These will later be moved to Canada's National Laboratory for Particle and Nuclear Physics (TRIUMF) where UCN densities as high as 5×10^4 cm^{-3} are expected [51]. With the larger proton beam intensity available at TRIUMF, the collaboration attempts to ultimately reach the level of 10^{-28} $e\,$cm.

An alternative approach to the use of stored UCNs with externally applied electric fields is the exploitation of high electric fields inside crystals where the magnitudes can be several orders of magnitude larger than in vacuum. The spin rotation is measured by diffraction of a cold neutron beam. Using a prototype setup [52] it has been argued that this technique can compete with the present level of sensitivity in a measuring time of about 100 days.

Considering the status of all these projects, it is likely that the experiment running at the UCN spallation source at PSI will be the first among them to produce a new improved limit on the neutron EDM.

3.2.3. Other hadrons

The specific conditions of the frozen spin method in a storage ring mentioned above, can possible be met with other charged particles. Based on this scheme, a new experiment has been proposed at BNL [54] to search for the deuteron EDM at the level of 10^{-29} $e\,$cm in one year. The measurement considers 1 GeV/c longitudinally polarized deuterons in a storage ring of about 85 m circumference, with magnetic dipole fields of 0.5 T.

A scheme to measure the proton EDM in a storage ring has also been recently proposed [53]. The size of the ring would be about 240 m circumference with radial electrostatic bend sections. The proton spin state would be probed with internal polarimeters based on proton scattering on a C target. The anticipated sensitivity level is similar to that for the deuteron but the two systems have complementary sensitivities to CP-odd effects (Table 1).

3.2.4. Diamagnetic atoms

Measurements of EDMs in atoms with closed electron shells mostly probe the nuclear EDM as well as T-violating interactions between the electrons and the nucleus. The most sensitive measurement in diamagnetic atoms have been those in ^{199}Hg [13] that resulted in the most precise EDM measurement so far among all systems (Table 2). This measurement sets also the present limit on the proton EDM. As stated above (Section 2), accidental degeneracies in the atomic structure, the existence of nuclear octupole deformations, as well as relativistic effects can strongly enhance P- and T-violating effects. This has motivated several new projects for the measurements of EDMs in atoms of heavy isotopes like Rn and Ra, which have no stable isotopes and require therefore special preparation techniques.

The cooling and trapping of neutral ^{225}Ra and ^{226}Ra atoms has recently been established at Argonne National Laboratory [55] as a step towards an EDM measurement of the ^{225}Ra atom ground state [56]. For the preparation of the experiment, an intense ^{229}Th laboratory source is used to produce a 2 mCi ^{225}Ra activity. A different cooling scheme has been demonstrated at the Kernfysisch Versneller Instituut in Groningen with Ba atoms [57] with the purpose to be applied to Ra isotopes. Nuclear structure studies as well as developments in spin-exchange polarization techniques are also in progress at TRIUMF [58] for an EDM measurement in ^{223}Rn.

Recent calculations indicate [59] that the ^{229}Pa atom EDM should be a factor of 40 larger as compared to that of ^{225}Ra. In this context, the new generation of radioactive ion beam facilities like the Facility for Rare Isotope Beams (FRIB) in East-Lansing, Michigan, are expected to provide abundant quantities of such short lived heavy isotopes for EDM searches.

3.2.5. Paramagnetic atoms and molecules

In atoms with an unpaired electron, the two most sensitive measurements have been performed in Cs [60], with gas vapor in cells, and in ^{205}Tl [14] with counter propagating beams. In this second experiment, a Na beam, parallel to the Tl beam, served as co-magnetometer to control systematics effects.

Several new projects consider improvements in sensitivity for the Cs EDM. For radioactive systems, a measurement in paramagnetic ^{210}Fr atoms has been proposed [61], for which the cooling and trapping is in preparation at RCNP in Osaka.

Due to their large polarizability and closely spaced opposite parity states, diatomic molecules can display large enhancements to CP-violating effects. The first measurement of this kind to determine the electron EDM was carried out with YbF molecules at Imperial College London [62]. The result was limited by statistics but demonstrated the power of the method. The group has made progress using the cold pulsed molecular beam [15] that resulted in an improved level of precision for the electron EDM, $d_e = (-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{sys}}) \times 10^{-28}\ e\,\text{cm}$.

The PbO molecule was pointed out to be also a potentially sensitive system. The Yale group made recent progress in the preparation of oriented states and detection of the evolution of spin-alignment [63]. Another experiment is in preparation using a cold beam of ThO molecules [64] and it is argued there that the current statistical sensitivity on the electron EDM could be improved my as much as three orders of magnitude. More recently it has been proposed [65] to use molecular ions trapped in an RF trap and cooled to cryogenic temperatures. It is expected that larger effective electric fields as well as longer coherence times could be achieved this way.

4. Conclusions

The searches for non-zero EDMs are essential for the understanding of CP violation in fundamental interactions. There are strong expectations that the current generation of ongoing and planned EDM experiments will finally yield non-zero results. The identification of the nature of the fundamental CP-violating mechanisms requires the study of EDMs in various systems together with complementary results from future collider experiments. In addition to recent attempts aiming at improving the current level of sensitivity for the neutron, atoms and molecules, several projects are being considered and new concepts have been proposed to measure EDMs in other systems, including charged particles or systems composed of radioactive species. Further collaborative efforts between experimentalists and theorists will sharpen the searches to unravel the new sources of CP violation.

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