Metastable D-state spectroscopy and laser cooling of barium
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Chapter 2

Time Reversal Symmetry and Electric Dipole Moments

The fundamental discrete symmetries Charge conjugation (C), Parity (P) and Time reversal (T) are accommodated in the Standard Model [7]. The violation of parity symmetry in the weak interactions [19, 20] observed in the experimental findings can be well described in the SM but it cannot account for the physical origin of this symmetry breaking. The effects of CP or T symmetry breaking are typically small compared to the dominating electromagnetic phenomena. The observation of these effects requires state-of-the-art, high precision experiments in conducting and theoretically analyzing them. To understand these symmetries and most importantly their origin, is a driving force of experimental particle physics. Searches for a permanent electric dipole moment (EDM) of a fundamental particle belongs to this category. Such experiments play a pivotal role, because an EDM of a fundamental particle implies that the time reversal symmetry T and parity P is violated.

In the Standard Model the violation of the combined charge conjugation C and parity P first observed in the neutral $K - \bar{K}$ meson decay is explained [23]. It can be described with a phase in the Cabibbo-Kobayashi-Maskawa matrix that accounts for quark mixing. Within the SM the observed CP-violation leads to EDMs too small to be seen in the current experiments (see Fig. 2.1). In contrast there exist other speculative theories such as SUper SYmmetry (SUSY) [24], Technicolor [25, 26], Left-Right symmetric models [27] that are possible extensions to the SM. These are much favored as candidates for new physics beyond the Standard Model as the size of EDMs could be large enough to be observed at the current experimental sensitivity. An EDM could be induced in various parti-
Chapter 2. Time Reversal Symmetry and Electric Dipole Moments

Figure 2.1: (a) Mechanism responsible for the electric dipole moment of the neutron in a one-loop diagram in the Standard Model. The dark blob indicates the CP-violating $\pi NN$ interaction [figure from [21]]. (b) An example of a three-loop quark contribution to the electron-photon vertex in the Standard Model. The cross denotes a mass insertion [figure from [22]].

Cles and bound systems that is sufficiently large to be observed experimentally. In general this will be the case for any model that predicts fermion compositeness and new particles (see Fig. 2.2). To explore all these possibilities we need to investigate several experimentally accessible systems to unravel the underlying SM extensions.

2.1 Electric Dipole Moment

A fundamental particle can have an intrinsic EDM only if T and P are violated [7]. The charge $q$ separated from a charge $-q$ by a distance $r$ creates an EDM $D \sim qr$. The violation of fundamental discrete symmetries P and T by a particle with a permanent EDM is depicted in Fig. 2.3. The EDM would necessarily lie along its spin axis because only one vector can be defined in a quantized system. Under space inversion ($P : r \rightarrow -r$) the quantity $D$ changes direction and the particle spin direction remains unchanged. Time reversal ($T : t \rightarrow -t$) changes the spin direction but leave the $D$ direction unchanged. This results in a particle with the opposite direction of the EDM relative to the spin. Thus, if time reversal is a good symmetry, particles with spin would produce degenerate states with either $D$ aligned parallel or anti-parallel to the spin.

Principle of Measurement

The most frequently applied experimental method to measure the dipole moment $d$ of a particle is to apply an electric field $E$ perpendicular to the particle spin
2.1. Electric Dipole Moment

A variety of theoretical speculative models exist in which an EDM could be induced in fundamental particles and composite systems. Through different mechanisms or a combination of them, an EDM would be experimentally accessible [from [28]].

Figure 2.2: A variety of theoretical speculative models exist in which an EDM could be induced in fundamental particles and composite systems. Through different mechanisms or a combination of them, an EDM would be experimentally accessible [from [28]].

(ensemble average) and look for spin precession. In practice, most of the EDM experiments employ the scheme developed by Purcell et al. [29]. The particle with spin $I$ under study is placed in external electric and magnetic fields $E$ and $B$. The moment $d$ interacts with electric field $E$. This contribution can be separated from the magnetic interaction term $-\mu \cdot B$ by reversing the electric field relative to the magnetic field. The Hamiltonian for the interactions of the magnetic and electric dipole moments for such a particle may be written as

$$H = (-dE + \mu B) \cdot \frac{I}{|I|},$$

(2.1)

where $d$ and $\mu$ are the electric and magnetic dipole moments and $I$ is the spin. The magnetic dipole moment $\mu$ is defined as

$$\bar{\mu} = g \frac{e\hbar}{2mc} I,$$

(2.2)

where $e$ is the charge of the electron, $g$ is the gyromagnetic ratio, $\hbar = h/2\pi$, $h$ is Planck constant, $I=(\hbar/2)\cdot\sigma$, $\sigma$ is Pauli matrix, $m$ is the mass of a particle, $c$ is the velocity of light, and $\vec{I}$ is the spin of a particle. In Dirac’s theory, the gyromagnetic ratio $g$ is 2 for point-like spin 1/2 particles. Radiative corrections
Figure 2.3: Particle with spin angular momentum $I$ and dipole moment $D$ under parity $P$ and time reversal $T$. In each case, the result produces a different state with either EDM parallel or anti-parallel to $I$.

give rise to the anomalous magnetic moment $a = (g - 2)/2 \approx \alpha/2\pi \simeq 1/860$. This deviates from the Dirac value of 2 and the deviation can be explained using quantum electrodynamics (QED). For composite objects the $g$-factor reflects the internal structure of these systems.

Analogously, the electric dipole moment is defined as

\begin{equation}
\vec{d} = \eta \frac{e\hbar}{2mc} \vec{I},
\end{equation}

where $\eta$ is the quantity that is derived from the atomic physics experiments. In Dirac theory $\eta$ is zero. In the SM $\eta \neq 0$, but is too small to be observed in presently possible experiments. Only in SM extensions measurable values have been predicted.

If $t$ is replaced by $-t$, $E$ does not change sign whereas $B$ and $I$ both do. Therefore, under time reversal symmetry the Hamiltonian $H$ changes if $d \neq 0$. Experimentally, the difference in Larmor precession frequencies with the electric field parallel ($+$) and anti-parallel ($-$) to the magnetic field can be measured. The difference is the EDM signal given by

\begin{equation}
\delta \nu = \frac{2dE}{\hbar} \frac{I}{|I|},
\end{equation}
$\nu$ is the spin resonance frequency.

The measurement of an EDM is a precession frequency measurement like an atomic clock. The magnetic part is well known and the small electric moment contribution has to be determined. For this atomic physics methods are well suited. An important parameter in an EDM experiment is the ultimate sensitivity of the method. The sensitivity $\delta d$, which is the statistical uncertainty in the measured EDM is given by

$$\delta d = \frac{h}{2E\sqrt{\tau NT}},$$

(2.5)

where $E$ is the magnitude of the applied effective electric field, $\tau$ is the spin coherence time, $N$ is the number of atoms under study and $T$ is the total measurement time.

The first experimental search for a permanent EDM of a fundamental particle, the neutron, was initiated almost six decades ago by Purcell and Ramsey [29]. This has led to numerous experimental measurements in various systems as well as theoretical predictions. A review on experimental and theoretical developments on EDMs has been given by Khriplovich and Lamoreaux [7] and several recent articles [22, 30, 31]. Various systems are being studied, aiming at different sensitivities to search for EDMs. Among them, the neutron and the electron take the larger share of the experimental activity.

### 2.2 EDM in Neutral Particles

#### 2.2.1 The Neutron

In the initial neutron EDM experiment by Smith et al. [32] a neutron beam was used. It was guided along crossed $E$ and $B$ fields. The precession frequency of the neutron spin was measured by the method of separated oscillatory fields [33]. The main limitation in these experiments arose from the motional magnetic field, as $B$ and $E$ were not aligned perfectly along the entire length of the apparatus. With time, experimenters used ultra-cold neutrons that can be stored in magnetic bottles for hundreds of seconds. In bottle experiments motional magnetic fields average out during the course of the measurement, since the neutrons average velocity is close to zero.

The two currently active neutron EDM experiments are carried out by the Gatchina and Grenoble groups in addition to the plans at PSI and LANSCE. The Gatchina group reported a value of $d_n=(2.6\pm4.0\pm1.6)\times10^{-26}$ ecm for the neutron EDM with separate statistical and systematic errors [34]. They used two
adjacent neutron bottles with opposite electric fields to cancel common magnetic field drifts. In 2006, the Grenoble group obtained a result $d_n < 3.0 \times 10^{-26}$ ecm [35]. They used ultra cold neutrons stored in traps. Using a cohabiting atomic-mercury magnetometer spurious signals from the magnetic field fluctuations were reduced. These results give an adopted upper limit for the neutron EDM, which is $< 3 \times 10^{-26}$ ecm.

2.2.2 Atoms

Paramagnetic Atoms

In the case of neutral atoms a quantity called nuclear Schiff moment [36] plays an important role. If we consider the neutral atom to have a point-like nucleus, then an external electric field at the nucleus is screened exactly due to rearrangement of the atomic electrons, which leads to no linear Stark effect (see Fig. 2.4). When this theorem is applied to neutral atoms the assumptions are not exactly satisfied because: the atomic electrons are relativistic, the atomic nucleus has a finite size and the electromagnetic interaction between electrons and nucleus has magnetic components. This gives rise to the Schiff moment. It consists of two parts: one is due to the P and T-violating nucleon-nucleon interaction and the other is due to core polarization via proton-neutron strong residual interaction the proton dipole moment contributes to the Schiff moment [31]. Therefore a measured atomic
EDM is a combined manifestation of these effects.

After the discovery of CP-violation in $K$ mesons [23] it was pointed out by Sandars [37] that in heavy atoms magnetic spin-orbit interactions become quite significant. Careful calculations revealed that in heavy paramagnetic atoms the atomic EDM increases as

$$d_a \propto d_e \alpha^2 Z^3.$$  \hspace{1cm} (2.6)

Detailed calculations show that the atomic EDM actually can be several hundred times larger than the EDM of a bare electron.

To measure the electron EDM the Berkeley group used a thermal atomic beam of thallium, a heavy paramagnetic atom and employed the technique of Ramsey separated oscillatory fields to measure the Larmor frequency [38, 39]. The motional magnetic fields were cancelled by using two oppositely directed atomic beams going through the same set of entrance and exit slits, which allows for cancellation of the first-order motional field associated with misalignment of $B$ and $E$ fields. They reported a limit on the electron EDM of $d_e < 1.6 \times 10^{-27}$ ecm [39].

**Diamagnetic Atoms**

The other type of atoms used to search for electric dipole moments associated with the nuclei are diamagnetic atoms. They have zero electronic angular momentum in the ground state and non-zero nuclear spin. Here, again the Schiff moment plays a dominant role. The Schiff moment induces an atomic EDM that is smaller than the EDM of a bare nucleus. But, it was pointed out by Khriplovich and co-workers [40] that in addition to the EDM of the valence nucleon the Schiff moment has a large contribution from the CP-odd nuclear forces that add coherently in the nucleus.

The most sensitive experiments of this type were carried out with the $^{199}$Hg atoms at the university of Washington, Seattle. The $^{199}$Hg atom is a good system in various aspects because it is heavy ($Z = 80$) (see Eq. 2.6), has spin $I = 1/2$, has long coherence time and can be probed optically. The experimental limit of $d(^{199}\text{Hg}) = 2.1 \times 10^{-28}$ ecm is the best limit for an EDM to date [8,41]. Recently, the experiment has been upgraded to improve the sensitivity by a factor of 5.

### 2.2.3 Symmetry Violation in Radium

**Electric Dipole Moment**

Radium, a heavy alkaline earth radioactive element, has attracted much theoretical as well as experimental attention in the recent past. Calculations show that it
is a potential candidate for searches of a permanent EDM because of its electronic and nuclear structure. This is because the effects of time invariance and parity violation are inversely proportional to the distance between opposite parity energy levels \([9, 12, 13]\). In the radium atom the \(7s6d \, ^3D_2\) and the state \(7s7p \, ^3P_1\) are separated only by 5 cm\(^{-1}\) which are based on a single measurement by Rasmussen in 1934 \([42, 43]\). The energy level scheme (Fig. 2.5) is according to the available atomic level data \([14]\). The other factors that lead to enhancement in radium are the large value of the nuclear charge \(Z = 88\) (the P and T-odd effects increase with \(Z\) faster than \(Z^2\)). Some of the radium nuclei have octupole deformation. This can be observed in the nuclear level scheme of \(^{225}\text{Ra}\) nucleus, which is shown in Fig. 2.6. The collective T, P-odd moments in octupole deformed nuclei are expected to be much greater than the same moments with spherical nuclei.

The atomic electric dipole moment appears due to the interaction between the

Figure 2.5: Level diagram of the radium atom with the wavelengths (vacuum) in nm of the transitions relevant for laser spectroscopy, laser cooling and trapping and for an EDM experiment. The wavelengths correspond to spectroscopic data given in reference [14]. The thickness of the lines indicate the strength of the transitions.
atomic electrons and the nuclear T, P-odd moments like the magnetic quadrupole moment, the Schiff moment and the electric octupole moments. These effects can also appear due to P, T-odd nuclear spin-dependent electron-nucleus interactions. The atomic EDM $d$ is given as [9]

$$d = 2^{\langle 7s6d_{3/2}, J = 2 \mid H_M \mid 7s7p_{1/2}, J = 1 \rangle \langle 7s7p_{1/2}, J = 1 \mid -er \mid 7s6d_{3/2}, J = 2 \rangle} / (E_1 - E_2),$$

where $H_M$ is the Hamiltonian of the magnetic interaction between the nuclear magnetic quadrupole moment and the atomic electrons, $E_1 = 13994$ cm$^{-1}$ ($7s6d_{J^P = 2^+}$) and $E_2 = 13999$ cm$^{-1}$ ($7s7p_{J^P = 1^-}$) and $-er$ is the dipole operator between $p$ and $d$ orbitals. The atomic EDM produced by the T, P-odd nucleon-nucleon interaction [9] is
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\[ d \simeq 2 \times 10^{-20} \eta \ \text{ecm} \quad (2.8) \]

where \( \eta \) is a dimensionless constant for the T, P-odd nucleon-nucleon interaction.

The atomic EDM can also be produced by the nuclear Schiff moment. The enhancement is due to the configuration mixing between the 7s and 7p\(_{1/2}\) states (for example, include mixing between the 7s6d and 7p7p configurations). The estimate of the atomic EDM due to the Schiff moment contribution comparable to the magnetic quadrupole contribution has been calculated [9] as

\[ d \simeq 5 \times 10^{-20} \eta \ \text{ecm}. \quad (2.9) \]

The above value is \( 10^5 \) times larger than the EDM of the Hg atom that was measured [8] that gives the present best limit on \( \eta \), which is \( 4.2 \times 10^{-9} \).

The octupole deformation of some of the radium nuclei, e.g., \(^{225}\text{Ra}\), may lead to a factor 50 - 500 enhancement of the nuclear Schiff moment w.r.t the \(^{199}\text{Hg}\) atom [11,46–49]. In this case, the nucleus has no longer the reflection symmetry, which can be seen in Fig. 2.7. Due to this one can observe rotational bands having states with positive and negative parities linked by strong dipole transitions [44]. The octupole deformation will have large Schiff moments because a large number of nucleons will contribute to the moments. In Fig. 2.8 we show the potential of radium with respect to the upper limits set by the experiments with various systems and constraints set on various models.

Figure 2.7: An example of a nucleus with an octupole deformation. The opposite parity states exist in symmetry breaking pear-shaped nucleus, which has no reflection symmetry [taken from [45]].
2.2. EDM in Neutral Particles

Figure 2.8: The progress in the experimental upper limits on EDMs in various systems with time. The values shown are the best upper limits for proton, neutron, electron and mercury experiments and their constraints on various theories beyond the Standard Model. The Standard Model limit for the electron is shown with the potential of radium in this competitive field [50].

Parity Non-Conservation Effects

For completeness we mention further the advantages of radium in the field of parity studies, because this research may also benefit from cold and trapped atoms. The SM can be verified by the observation of neutral currents through parity non-conservation in atoms. The neutral weak interaction that does not conserve parity is mediated by the exchange of a $Z^0$ boson between an electron and a quark inside the nucleus. In the SM, this spin-independent weak interaction is described by a Hamiltonian given by [51]

$$H_{PNC} = \frac{1}{2\sqrt{2}}G_F Q_W \gamma^5 \rho(r),$$

(2.10)

where $G_F$ is the Fermi constant, $\rho(r)$ is the nuclear density, and $\gamma^5$ is the Dirac matrix. The weak charge of the nucleus, $Q_W$, is analogous to the electric charge for the electromagnetic interaction. For an atom with atomic number $Z$ and $N$ neutrons, the value of $Q_W$ [52] at tree level\(^1\) without radiative corrections is given

\(^1\)Tree level is the lowest order of the theory
by

\[ Q_W = Z(1 - 4 \sin^2 \theta_W) - N, \] (2.11)

where \( \theta_W \) is the Weinberg angle. This \( \gamma-Z^0 \) mixing angle \( Q_W \) is the atomic physics parameter to be measured and compared to the standard model. Any deviation from the tree-level value of \( Q_W \) indicates or signals a breakdown in the standard model predictions.

Atomic parity non-conservation (PNC) also occurs due to the nuclear anapole moment \[51\]. The anapole moment is a parity-odd, time reversal-even moment of the \( E1 \) projection of the electromagnetic current. It is enhanced in heavy nuclei, increasing as \( A^{2/3} \), where \( A \) is the mass number, and thus increasing in proportion to the nuclear surface area. The net result is that anapole contributions to the weak radiative correction will dominate. The Colorado group \[53\] reported PNC measurement in \(^{133}\)Cs at 0.35\% level, from which a nuclear spin dependent PNC signal was extracted. This spin dependence is well above the expected signal from \( Z^0 \) exchange alone but is comparable with the enhancement expected from anapole effects. For atomic parity violation a higher experimental accuracy might be possible from experiments using francium isotopes and isotopes of barium and radium ions.

Radium can be used to measure the parity non-conservation effects. The closeness of the opposite parity levels and the large nuclear charge \( Z \) give rise to the parity-violating amplitude \( E1_{PV} \) in radium about 100 times larger than a similar amplitude in cesium \[9,12\]. They find that this anapole induced amplitude makes a dominant contribution to the total parity-violating amplitude in radium. This may be an advantage, since in cesium the anapole contribution has to be separated from the weak charge contribution, which is two orders of magnitude larger than the anapole contribution. The weak charge contribution in radium can be neglected because the states \( 7s7p \,^3P_1 \) and \( 7s6d \,^3D_2 \) have different electron angular momenta \( J = 2 \) and \( J = 1 \) and can not be mixed by the weak nuclear spin independent interaction.

Due to the above discussed advantages our group works towards an EDM experiment with several radium isotopes \[54\]. Also a group at the Argonne National Laboratory, USA has plans to use \(^{225}\)Ra for the same purpose \[55\]. Since the EDM of radium depends on the atomic and nuclear properties we give a review of the known experimental data and theoretical efforts in Chapter 4. Especially theorists have become interested in radium. Their results show the importance of the knowledge of the atomic wavefunctions in order to evaluate the sensitivity to an EDM and the available experimental data is not yet sufficient.
2.2.4 Molecules

Molecules known as polar molecules have large intrinsic EDMs. They are used to search for EDM of an electron [22]. In a simplified picture of a molecule, they have pairs of nearly degenerate states with opposite parity. Since their energy splitting is less than the thermal energy $kT$ at room temperature, the two states act practically like a two-fold-degenerate ground state. When an external electric field $E$ is applied, the two states of opposite parities, $|+\rangle$ and $|-\rangle$, mix with each other and form new energy eigenstates, $|r\rangle \approx (|+\rangle+|-\rangle)/\sqrt{2}$ and $|l\rangle \approx (|+\rangle-|-\rangle)/\sqrt{2}$ with energy eigenvalues [22]

$$E_{r,l} = \frac{1}{2}(E_+ + E_-) \pm \frac{1}{4}((E_+ - E_-)^2 + (e\langle r \rangle \cdot E)^2)^{1/2}, \quad (2.12)$$

where $\langle r \rangle$ is the transition-matrix element between $|+\rangle$ and $|-\rangle$. Because $E_{\pm}$ are almost degenerate, $e\langle r \rangle \cdot E$ dominates inside the square root term in Eq. 2.12, and the energy eigenvalues are given approximated by

$$E_{r,l} = \frac{1}{2}(E_+ + E_-) \pm e\langle r \rangle \cdot E, \quad (2.13)$$

In this approximation the energy shift is linearly dependent on $E$, the proportionality constant is traditionally called the “permanent EDM” of the molecule. But, this EDM is not an indication of P and T-violation. If measurements are carried out with an infinitesimally weak $E$ at zero temperature, one will find only a quadratic dependence of the energy eigenvalues on $E$, that is,

$$E_{r,l} = E_+ \pm (e\langle r \rangle \cdot E)^2/(E_+ - E_-) + ... \quad (2.14)$$

by a power series expansion in $E$. Thus there is no linear dependence on $E$ of the energy shift. If $T$ invariance holds, a molecule acquires only an induced EDM, which is enhanced by a small energy difference between the opposite parity states. But a permanent EDM causes a linear Stark effect even for an infinitesimally weak $E$, which is a genuine signature of P and T-violation.

Two types of polar molecules, called paramagnetic and diamagnetic, are being used in the search for electron EDMs. In these molecules, large polarization can be achieved with modest external fields that greatly enhance an EDM. The observable energy shifts caused by an electron EDM may be 100-1000 times greater than in paramagnetic atoms. Paramagnetic molecules are obtained in two ways. One way is by using molecules that are paramagnetic in their ground states e.g., thallium fluoride (TlF) [56] and ytterbium fluoride (YbF) [57]. The other way is by populating a paramagnetic state of a diamagnetic molecule in the ground
state e.g., lead oxide (PbO) [58]. The former are thermally and chemically unstable (chemical radicals), and the experiments must be carried out in beams. This is a constraint to achieve a high production rate. The sensitivity reported for the YbF molecule measurement is $d_e = (-0.2 \pm 3.2) \times 10^{-26}$ ecm, limited by counting statistics, with the future possible sensitivity level of $1 \times 10^{-27}$ ecm [57].

The second approach uses diamagnetic molecules that are pumped to a paramagnetic state. The advantage is that these molecules are thermally and chemically stable. They can be stored in a cell, which gives this experiment a large advantage in sensitivity due to the large number of molecules. With a proposed ultimate sensitivity of $d_e < 10^{-31}$ ecm for PbO molecule, the EDM limit can be improved by 4 orders of magnitude below the current limit set by the thallium experiment [58].

### 2.3 EDM in Charged Particles

One might assume that charged objects, like ions would not be suited for searches for EDMs since they are accelerated when placed in an electric field. Recently, a very novel idea was introduced for measuring an EDM of a charged particle directly. This idea originates from the muon g-2 experiment [59, 60]. For such experiments the high motional electric field is exploited, which a charged particle at relativistic speed experiences in a magnetic storage ring. In such a setup the Schiff theorem can be circumvented, because of the non-trivial geometry of the problem [31]. With an additional radial electric field in the storage region the spin precession due to the magnetic moment anomaly can be compensated, if the effective magnetic anomaly $a_{eff}$ is small, i.e., $a_{eff} \ll 1$.

#### 2.3.1 Muon

The principle described above was first considered for muons. For longitudinally polarized muons injected into the storage ring an EDM would express itself as a spin rotation out of the orbital plane. The spin orientation can be found by measuring the distribution of electrons from muon decay. An EDM would appear as time dependent change of ratio of the counting rate above or below the orbit plane. The upper limit reported on muon EDM is $<2.8 \times 10^{-19}$ ecm [61]. For the possible muon beams at the future J-PARC facility in Japan a sensitivity of $10^{-24}$ ecm is expected [60, 62]. In such an experiment the flux is a major limitation. For models with non-linear mass scaling of EDM’s such an experiment would already be more sensitive to some certain new physics models than
### Table 2.1: Limits on permanent EDMs $d$ for electrons (e), muons ($\mu$), protons (p), neutrons (n) and the mercury atom ($^{199}$Hg).

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<tbody>
<tr>
<td>e</td>
<td>$&lt;1.6 \times 10^{-27}$ (90% CL) [39]</td>
<td>$10^{11}$</td>
<td>$\lesssim 1$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$&lt;2.8 \times 10^{-19}$ (95% CL) [61]</td>
<td>$10^8$</td>
<td>$\lesssim 200$</td>
</tr>
<tr>
<td>p</td>
<td>$-3.7(6.3) \times 10^{-23}$ [66]</td>
<td>$10^7$</td>
<td>$\lesssim 10^5$</td>
</tr>
<tr>
<td>n</td>
<td>$&lt;3 \times 10^{-26}$ (90% CL) [35]</td>
<td>$10^4$</td>
<td>$\lesssim 30$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$&lt;2.1 \times 10^{-28}$ (95% CL) [8]</td>
<td>$\lesssim 10^5$</td>
<td>various</td>
</tr>
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2.3.2 Deuteron

Another particle that is being considered actively in the recent past is the deuteron, the simplest nucleus [63–65]. Here an EDM could arise not only from a proton or a neutron EDM, but also from CP-odd nuclear forces. It was shown very recently that in certain scenarios the deuteron can be significantly more sensitive than the neutron. This is evident for the case of quark chromo-EDMs $d_d^c$ and $d_u^c$ of the up and down quarks yield $d_D = -4.67 d_d^c + 5.22 d_u^c$ and $d_n = -0.01 d_d^c + 0.49 d_u^c$. Due to its rather small magnetic anomaly the deuteron is a particularly interesting candidate for a ring EDM experiment and a proposal with a sensitivity of $10^{-27}$ ecm exists [60]. In this case scattering off a target will be used to observe a spin precession.

Some experimental upper limits on EDMs in various systems with different sensitivities are summarized in Table 2.1.

2.3.3 T-violation Searches other than EDMs

Time reversal violation (TRV) searches are also being carried out other than through the search for EDMs [67]. The approach that is complementary for searching of TRV is through certain angular correlation studies in $\beta$-decays [68–70]. In $\beta$-neutrino correlation studies the $R$ and $D$ coefficient (for spin polarized nuclei) [68] offers to observe new interactions in a region of potential new physics
which is similar to EDM searches. With the combined use of laser cooling and trapping technique and recoil ion momentum spectroscopy [71], the investigation of β-decay of the radioactive species can be carried out with high precision.

2.4 Experimental Methods for EDM Searches

In this section the advantages of EDM experiments with cold atoms in atom traps over traditional methods is presented. So far, atomic EDM experiments have been conducted in vapor cells [8, 39] and with atomic beams [38, 72]. Both methods have their advantages and disadvantages. In the case of vapor cell experiments high atomic density could be achieved in a smaller region and with minimum motional magnetic field effect. One can achieve long spin coherence times and does not need ultra high vacuum apparatus. The disadvantage is the spurious magnetic fields due to leakage currents. In the case of beam experiments the dominant systematic error is the motional magnetic field, less interaction time but high electric fields can be applied over the length of the apparatus.

With the laser cooling and trapping technique, EDM measurements using an optical trap are superior to the above measurement methods. Over the cells, ultra high vacuum suppresses spurious magnetic fields due to leakage currents and allows for application of high electric fields. Smaller sample region also allows for large external electric field for the measurement of EDM. Over the atomic beams, zero average motional magnetic field $v \times E$ and large density of atoms for larger EDM signal can be obtained. The advantages over both of the other methods are low in-homogeneity of external fields in the sample region and long spin relaxation lifetimes.

The basic EDM experimental setup using traps consists of a magneto-optical trap to initially cool and trap the atoms. Subsequently they can be transferred to an optical dipole trap (FORT - Far Off-Resonance Trap), where the actual EDM measurement would be performed. Also a fountain setup like for atomic clocks would be an option. Systematic effects due to orientation of static $B$ field relative to the polarization axis of the FORT laser beams have been investigated in [73]. They find the linear Stark shift can be minimized for a configuration in which the magnetic field is along the $z$-axis, $k$ along the $x$-axis, and the linear polarization of the light along the $y$-axis. Furthermore, in the case of nuclear spin $I=1/2$ nuclei the quadratic Stark shift is eliminated. In the case of alkali metal atoms a potential problem for an EDM measurement in a trap are the cold collisions that cause spin relaxation and lead to frequency shifts [74, 75].

Fermionic alkaline earth elements, having closed electronic shells with a $^1S_0$
ground state, such as $^{213,225}\text{Ra}$ ($I=1/2$), do not have these problems. When these atoms are spin polarized, the $s$-wave scattering cross-section will be zero, while higher scattering cross-sections minimize to zero at sufficiently low temperatures. With this, long spin coherence times could be achieved and collisional spin relaxation and three-body recombination rates could be reduced. With all these advantages EDM measurements using cold atoms and traps prove to be superior to the methods used currently.

2.5 EDMs As a Tool to Search for New Physics

Searches for EDMs can stringently test the Standard Model and set limits on the SM extensions or find physics beyond the SM. Many experiments are needed and possibly will allow to disentangle the findings in terms of the underlying possible SM extensions. New systems have been introduced recently for searches of EDMs. Among them, the radium atom seems to be a promising candidate because of various advantages over the systems studied and investigated currently in this competitive field. Radium allows to search uniquely both for nuclear and electron EDMs. New experimental techniques need to be developed to exploit this potential, which is shown in this thesis. This includes development of spectroscopic as well as cooling and trapping methods for neutral heavy alkaline earth atoms.