Searches for permanent electric dipole moments (EDMs) of fundamental particles render the possibility to discover New Physics beyond present Standard Theory. New ideas for experiments have come up recently which may allow to lower present limits substantially or even find unambiguous effects. Such are predicted by a variety of speculative models. The identification of potential sources for CP and T-violation will require to study several systems, which all have different sensitivity to possible mechanisms generating EDMs.

1. Introduction

The Standard Model (SM) provides a remarkable framework to describe observations in particle physics. Despite the success of the SM, a number of most intriguing questions remains in modern physics. Among those are the observation of exactly three generations of fundamental particles and the hierarchy of the fundamental fermion masses. In addition, the electro-weak SM has a rather large number of some 27 free parameters, which all need to be extracted from experiments\(^1\).

In modern physics - and in particular in the SM - symmetries play an important and central role. Whereas global symmetries relate to conservation laws, local symmetries yield forces.\(^2\) It is rather unsatisfactory that within the SM the physical origin of the observed breaking of discrete symmetries in weak interactions, e.g. of parity (P), of time reversal (T) and of com-
bined charge conjugation and parity (CP), remains unrevealed, although the experimental findings can be well described.

The speculative models beyond the present standard theory include such which involve Left-Right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity, technicolor and many more. Interesting candidates for an all encompassing quantum field theory are string or membrane (M) theories which in their low energy limit may include supersymmetry. Without secure experimental evidence to be gained in future all of these speculative theories will remain without status in physics, independent of their mathematical elegance and partial appeal. Experimental searches for predicted unique features of those models - such as breaking of symmetries - are therefore essential to steer theory towards a better and deeper understanding of fundamental laws in nature. Such experiments can be carried out in a complementary manner at high energy accelerators and also at lower energies - typically in the regime of atomic physics - in high precision measurements, such as EDMs searches.

2. Discrete Symmetries

In this article we are concerned with discrete symmetries. A permanent electric dipole moment (EDM) of any fundamental particle or quantum system violates both parity (P) and time reversal (T) symmetries. The violation of P is well established in physics and its accurate description has contributed significantly to the credibility of the SM. The observation of neutral currents together with the observation of parity non-conservation in atoms were important to verify the validity of the SM. The fact that physics over 10 orders in momentum transfer - from atoms to highest energy scattering - yields the same electro-weak parameters may be viewed as one of the biggest successes in physics to date. However, at the level of highest precision electro-weak experiments questions arose, which ultimately may call for a refinement.

The predicted running of the weak mixing angle \( \sin^2 \Theta_W \) appears not to be in agreement with observations. If the value of \( \sin^2 \Theta_W \) is fixed at the \( Z^0 \)-pole, deep inelastic electron scattering at several GeV appears to yield a considerably higher value. A reported disagreement from atomic parity violation in Cs has disappeared after a revision of atomic theory. A new round of experiments is being started with the \( Q_{weak} \) experiment at the Jefferson Laboratory in the USA. For atomic parity violation in principle higher experimental accuracy will be possible from experiments using Fr
Table 1. Some actual limits on EDMs and the improvement factors necessary in experiments to reach SM predictions. It appears that for electrons, neutrons and muons the region where speculative models have predicted a finite value for an EDM can be reached with presently proposed experiments in the near future.

| Particle | Limit/Measurement [e cm] | Method employed in latest experiment | Standard Model Limit [factor to go] | Possible New Physics [factor to go] |
|----------|--------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| e        | < 1.6 × 10^{-27}        | Thallium beam                      | 10^{11}                            | ≤ 1                                 |
| μ        | < 2.8 × 10^{-19}        | Tilt of precession plane in anomalous magnetic moment experiment | 10^8                               | ≤ 200                               |
| τ        | (-2.2 < d_τ < 4.5) × 10^{-17} | Electric form factor in e^+e^- → ττ events | 10^7                               | ≤ 1700                              |
| n        | < 6.3 × 10^{-26}        | Ultra-cold neutrons                | 10^4                               | ≤ 60                                |
| p        | (-3.7 ± 6.3) × 10^{-23} | 120kHz thallium spin resonance     | 10^7                               | ≤ 10^5                              |
| Λ^0      | (-3.0 ± 7.4) × 10^{-17} | Spin precession in motional electric field | 10^{11}                            | 10^9                                |
| ν_{e,μ}  | < 2 × 10^{-21}          | Inferred from magnetic moment limits |                                    |                                      |
| ν_τ      | < 5.2 × 10^{-17}        | Z decay width                      |                                    |                                      |
| Hg-atom  | < 2.1 × 10^{-28}        | Mercury atom spin precession       | ≤ 10^5                             | various                             |

Note: Interesting systems such as deuterons and Ra atoms are not listed, because no experiments have been performed yet. However, higher sensitivity to non-SM EDMs has been predicted compared to neutrons (e.g. more than one order of magnitude for certain quark chromo EDMs and Hg atoms (e.g. more than three orders of magnitude for an electron EDM and two orders for nuclear EDMs) respectively.
isotopes$^{20,21}$ or single Ba or Ra ions in radiofrequency traps $^{22}$. Although the weak effects are larger in these systems due to their high power dependence on the nuclear charge, this can only be exploited after improved atomic wave function calculations will be available, as the observation is always through an interference of weak with electromagnetic effects.$^{23}$

The violation of the combined charge conjugation (C) and parity (P) operations has been observed first in the neutral Kaon decays and can be described with a phase in the Cabbibo-Kobayashi-Maskawa formalism$^{24}$. CP-Violation is particularly highly interesting through its possible relation to the observed matter-antimatter asymmetry in the universe. A. Sakharov$^{25}$ has suggested that the observed dominance of matter could be explained via CP-violation in the early universe in a state of thermal non-equilibrium and with baryon number violating processes.$^{b}$ CP violation as described in the SM is insufficient to satisfy the needs of this elegant model. This strongly motivates searches for yet unknown sources of CP-Violation.

### 3. Searches for Permanent Electric Dipole Moments

Excellent opportunities to find such new CP-Violation are provided through possible EDMs. With the assumption of CPT invariance CP- and T-violation can be considered equivalent$^{3}$ and therefore an EDM also violates CP. For all particles CP-Violation as it is known from the K and B mesons causes EDMs to appear through higher order loops $^{3}$. These are at least 4 orders of magnitude below the present experimental limits (see Table 1). Several speculative models foresee EDMs which could be as large as the present experimental bounds just allow.$^{c}$

EDMs have been searched for in various systems with different sensitivities (Table 1). The spectrum of activities has been frequently reviewed in the recent past.$^{3,28,29,30}$ A number of distinctively different precision experiments to search for am EDM in one or another system are under way and several ideas for significant improvements have been made public. Still, the electron and the neutron get the largest attention of experimental groups. In composed systems such as molecules or atoms fundamental particle dipole moments of constituents may be significantly enhanced$^{28}$. For the

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$^{b}$We note here that the existence of additional sources of CP-Violation is not a necessary condition to explain the matter-antimatter asymmetry. Other viable routes could lead through CPT violation and there without the need of thermal non-equilibrium.$^{26}$

$^{c}$Historically the non-observation of any EDM has ruled out more speculative models than any other experimental approach in all of particle physics.$^{27}$
electron significant enhancement factors are planned to be exploited such as those associated with the large internal electric fields in polar molecules.\textsuperscript{31}

The physical systems investigated fall in five groups, i.e. (i) 'point' particles (e, $\mu$, $\tau$), (ii) nucleons (n, p), (iii) nuclei ($^2$H, $^{223}$Fr, ...), (iv) atoms (Hg, Xe, Tl, Cs, Rn, Ra,...) and (v) molecules (TlF, YbF, PbO, ...), where each investigated object has its own particular advantages. Among the methods employed are (i) Classical approaches using optical spectroscopy of atoms and molecules in cells, as well as atomic and molecular beams or with contained cold neutrons, (ii) Modern atomic physics techniques such as traps, fountains and interference techniques; (iii) Innovative approaches involving radioactive species, storage rings, particles in condensed matter, 'masers', and more. It will remain to be seen, which of all these promising approaches will succeed in providing new limits or even find an EDM.\textsuperscript{4}

We must note that there is no preferred system to search for an EDM. In fact, many systems need to be examined, because depending on the underlying processes different systems have in general quite significantly different susceptibility to acquire an EDM through a particular mechanism (see Figure 1). An EDM may be found an "intrinsic property" of an elementary particle as we know them, because the underlying mechanism is not accessible at present. However, it can also arise from CP-odd forces between the constituents under observation, e.g. between nucleons in nuclei or between nuclei and electrons. Such EDMs could be much higher\textsuperscript{17} than such expected for elementary particles originating within the popular, usually New Physics models.

4. Some New Developments in the Field of EDM Searches

This highly active field of research benefited recently from a plurality of novel ideas. Those have led to new activities in systems not investigated so far. Among those are in particular radioactive atoms and charged particles.

4.1. Radioactive Systems

New facilities around the world make more short-lived radioactive isotopes available for experiments. Of particular interest is the Ra atom, which

\textsuperscript{4}An all encompassing review of all the relevant aspects and giving justice to all the new ideas in this rapidly growing field can not even be attempted in this article.
Figure 1. A variety of theoretical speculative models exists in which an EDM could be induced through different mechanisms or a combination of them into fundamental particles and composed systems for which an EDM would be experimentally accessible. Up to now very sensitive experiments were only carried out for composed neutral systems. A novel technique may allow to sensitively access EDMs also for charged fundamental particles and ions. (Figure adapted from C.P. Liu33.)
has rather close lying states of opposite parity. This accidental almost
degeneracy of the $7s7p^3P_1$ and $7s6d^3D_2$ states has led to the prediction of
a significant enhancement for an electron EDM$^{18}$ - much higher than for
any other atomic system. Further more, for many Ra isotopes their nuclei
fall are within in a region where (dynamic) octupole deformation occurs,
which also enhances the effect of a nucleon EDM substantially, i.e. by some
two orders of magnitude$^{19}$. From a technical point of view the Ra atomic
levels of interest for an experiment are well accessible spectroscopically and
the isotopes can be produced in sufficient quantities in nuclear reactions.
The advantage of an accelerator based Ra experiment is apparent, because
nuclear EDMs are only possible nuclei with spin and all Ra isotopes with
no-vanishing nuclear spin are relatively short-lived.\textsuperscript{32}

\textbf{4.2. Searches for EDMs in charged Particles}

A very novel idea was introduced recently for measuring an EDM of charged
particles directly. For such experiments the high motional electric field is
exploited, which charged particles at relativistic speed experience in a mag-
netic storage ring. In such a setup the Schiff theorem can be circumvented
(which had excluded charged particles from experiments due to the Lorentz
force acceleration), because of the non-trivial geometry of the problem\textsuperscript{28}.

With an additional radial electric field in the storage region the spin pre-
cession due to the magnetic moment anomaly can be compensated, if the
effective magnetic anomaly $a_{\text{eff}}$ is small, i.e. $a_{\text{eff}} << 1$.\textsuperscript{34}

The method was first considered for muons. For longitudinally polarized
muons injected into the ring an EDM would express itself as a spin rotation
out of the orbital plane. This can be observed as a time dependent (to first
order linear in time) change of the above/below the plane of orbit counting
rate ratio. For the possible muon beams at the future J-PARC facility in
Japan a sensitivity of $10^{-24}$ e cm is expected\textsuperscript{35,36}. In such an experiment
the possible muon flux is a major limitation. For models with nonlinear
mass scaling of EDM’s such an experiment would already be more sensitive
to some certain new physics models than the present limit on the electron
EDM\textsuperscript{37}. For certain Left-Right symmetric models a value of $d_\mu$ up tp to
$5 \times 10^{-23}$ e cm would be possible. An experiment carried out at a more
intense muon source could provide a significantly more sensitive probe to
CP violation in the second generation of particles without strangeness.\textsuperscript{e}

\textsuperscript{e}A New Physics (non-SM) contribution $a_\mu^{\text{NP}}$ to the muon magnetic anomali and a
The deuteron is the simplest known nucleus. 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 the deuteron can be in certain scenarios significantly more sensitive than the neutron. In equation (1) this situation is evident for the case of quark chromo-EDMs:

\[
\begin{align*}
    d_D &= -4.67 d^c_d + 5.22 d^c_u, \\
    d_n &= -0.01 d^c_d + 0.49 d^c_u.
\end{align*}
\]

It should be noted that because of its rather small magnetic anomaly the deuteron is a particularly interesting candidate for a ring EDM experiment and a proposal with a sensitivity of $10^{-27}$ e cm exists. In this case scattering off a target will be used to observe a spin precession. As possible sites of an experiment the Brookhaven National Laboratory (BNL), the Indiana University Cyclotron Facility (IUCF) and the Kernfysisch Versneller Instituut (KVI) are considered.

5. T-violation Searches other than EDMs

Besides EDMs there exist more possibilities to find T-Violation. Among those certain correlation observables in $\beta$-decays offer excellent opportunities to find such new sources. In $\beta$-neutrino correlations the 'D'-coefficient (for spin polarized nuclei) offer a high potential to observe new interactions in a region of potential New Physics which is less accessible by EDM searches. However, the 'R'-coefficient (observation of $\beta$-particle polarization) would explore the same areas as present EDM searches or $\beta$-decay asymmetry measurements. Such experiments are underway at a number of laboratories worldwide.

6. Conclusions

There is a large field of searches for EDMs on a large number of systems. Novel ideas have emerged in the recent past to use yet not studied systems and new experimental approaches, which have emerged in the recent muon EDM $d_\mu$ are real and imaginary part of a single complex quantity related through $d_\mu = 3 \times 10^{-22} \times (a^{NP}_\mu/(3 \times 10^{-9})) \times \tan \Phi_{CP} e cm$ with a yet unknown CP violating phase $\Phi_{CP}$. The problems around the SM model value for $a_\mu^{38,39}$, which cause difficulties for the interpretation of the recent muon g-2 experiment in terms of limits for or indications of New Physics, make a search for $d_\mu$ attractive as an important alternative, as the SM value is negligible for the foreseeable future.
past offer excellent opportunities to complement the more traditional experimental approaches on neutron-, atom- and electron-EDMs, which have yielded the best limits to date. Any successful search in the future will have to be complemented by experiments on other systems in order to pin down eventually the mechanisms leading to the observed EDMs.

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