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Measurement of Permanent Electric Dipole Moments of Charged Hadrons in Storage Rings

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Abstract Permanent Electric Dipole Moments (EDMs) of elementary particles violate two fundamental symmetries: time reversal invariance ($\mathcal{T}$) and parity ($\mathcal{P}$). Assuming the $\mathcal{CPT}$ theorem this implies $\mathcal{CP}$ violation. The $\mathcal{CP}$ violation of the Standard Model is orders of magnitude too small to be observed experimentally in EDMs in the foreseeable future. It is also way too small to explain the asymmetry in abundance of matter and anti-matter in our universe. Hence, other mechanisms of $\mathcal{CP}$ violation outside the realm of the Standard Model are searched for and could result in measurable EDMs.

Up to now most of the EDM measurements were done with neutral particles. With new techniques it is now possible to perform dedicated EDM experiments with charged hadrons at storage rings where polarized particles are exposed to an electric field. If an EDM exists the spin vector will experience a torque resulting in change of the original spin direction which can be determined with the help of a polarimeter. Although the principle of the measurement is simple, the smallness of the expected effect makes this a challenging experiment requiring new developments in various experimental areas.

Complementary efforts to measure EDMs of proton, deuteron and light nuclei are pursued at Brookhaven National Laboratory and at Forschungszentrum Jülich with an ultimate goal to reach a sensitivity of $10^{-29} e\cdot$cm.

Keywords electric dipole moment · Standard Model · CP violation · matter–anti-matter asymmetry

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1 Introduction & Motivation

One of the great mysteries in particle physics is the dominance of matter over anti-matter in our Universe. The net baryon number is [1]

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = \left(6.1^{+0.3}_{-0.2} \cdot 10^{-10}\right) .$$

In the Standard Model (SM) this ratio is expected to be on the order of 10^{-18}. In 1967 Sakharov [2] formulated three prerequisites for baryogenesis. One of these is the combined violation of the charge and parity, $\mathcal{CP}$, symmetry. New $\mathcal{CP}$ violating sources outside the realm of the SM are clearly needed to explain this discrepancy of eight orders of magnitude.

For non-degenerate systems like for example elementary particles, including hadrons, an electric dipole moment is only possible if the two fundamental symmetries, parity $\mathcal{P}$ and time reversal invariance $\mathcal{T}$ are violated. Using the $\mathcal{CPT}$ theorem a violation of $\mathcal{T}$ is equivalent to $\mathcal{CP}$ violation.

$\mathcal{CP}$ violation is present in the Standard Model in two places. In the so called θ term of QCD which could in principle range from 0 to 2π. The fact that no hadronic EDM has been found up to now limits θ to an unnaturally small number of 10^{-10}. This is called the strong QCD problem. The second source is the complex phase parameter of the Cabibbo-Kobayashi-Maskawa matrix which would result in EDMs of the order of 10^{-31} to $10^{-32} e\cdot$cm for hadrons, much below experimental sensitivity reachable in the near future, whereas most of the extension of the Standard Model predict EDMs which are the range of future experiments [3, 4].

Tab. 1 shows current limits on hadron EDMs. There is no direct measurement of charged hadron EDMs reaching the sensitivity of the neutron measurement. The measurement of a single hadron EDM cannot decide on the source of $\mathcal{CP}$ violation (e.g. θ-term, beyond SM). It is thus mandatory to measure EDMs of various species of particles[5–8]. Methods to determine charged hadron EDMs with a sensitivity of $10^{-29} e\cdot$cm will be presented in the following. This subject is also addressed in [9].

Particle/Atom	Current Limit/$e\cdot$cm	Ref.
Neutron	$< 3 \cdot 10^{-26}$ $(90\% CL)$	[10]
^{199}Hg	$< 3.1 \cdot 10^{-29}$ $(95\% CL)$	
→ Proton	$< 7.9 \cdot 10^{-25}$	[11]
Deuteron	-	
^{3}He	-	

Table 1 Current limits of hadron EDMs.

2 Principle of the Measurement

The principle of every EDM measurement (be it atom, molecule, charged particle, ...) is the interaction of an electric field $\mathbf{E}$ with the dipole moment $\mathbf{d}$ of the particle. Since the spin is the only vector of an elementary particle defining a direction, the EDM has to be (anti-)parallel to the spin vector. Thus under the influence of an electric field the spin vector $\mathbf{S}$ gets tilted (with respect to the momentum vector) according to

$$\frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \mathbf{d} \times \mathbf{E}^* \,. \tag{1}$$

Here, $\mathbf{E}^*$ denotes the electric field in the particle rest frame.

A generic EDM measurement for a charged particle could thus look as indicated in Fig. 1, [12,13] [1]. Longitudinally polarized particles enter a storage ring. A radial electric field serves as a guiding field. An EDM will tilt the spin in the vertical direction. This vertical polarization component can be measured with the help of a polarimeter.

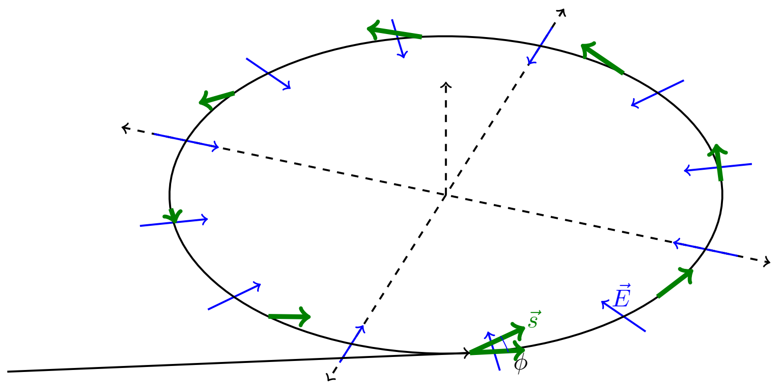

Fig. 1 Principle of an EDM measurement in a storage ring. Longitudinally polarized particles enter a storage ring. A radial electric field serves as a guiding field. An EDM will tilt the spin in the vertical direction. This vertical polarization can be measured with the help of a polarimeter (not shown in the Figure).

More generally in presence of electric and magnetic fields, and considering that particles also posses a magnetic moment $\boldsymbol{\mu} = 2(G+1)\frac{e\hbar}{2m}\mathbf{S}$ ($G = (g-2)/2$ being the anomalous $g-$factor), the spin motion is governed by the Thomas-BMT equation [16,17] (simplified by assuming $\mathbf{v}\cdot\mathbf{B} = \mathbf{v}\cdot\mathbf{E} = 0$):

$$\frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \mathbf{S} \times \boldsymbol{\Omega} \quad \text{with}$$
$$\boldsymbol{\Omega} = \frac{e\hbar}{mc}\left[G\mathbf{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\mathbf{E} \times \mathbf{v} + \frac{1}{2}\eta(\mathbf{E} + \mathbf{v} \times \mathbf{B})\right]. \tag{2}$$

[1] There are two (parasitic) measurements for charged particles: Λ [14] and muon [15].

Here $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic fields in the laboratory system. The dimensionless parameter η has been introduced via the relation $\mathbf{d} = \eta \frac{e\hbar}{2mc}\mathbf{S}$. The other variables have their usual meaning.

Taking eq. 2 as a starting point, different approaches are possible. They will be discussed in the following subsections. In general it is advisable to eliminate the terms proportional to G because spin motions caused by the magnetic moment are in general much larger than those caused by the tiny EDM effect.

2.1 Pure electric field

Using only an electric field (i.e. $\mathbf{B} = 0$) with the additional condition that $\left(G - \frac{1}{\gamma^2-1}\right) = 0$, eq. 2 reduces to

$$\frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \frac{e\hbar}{2mc}\eta \mathbf{S} \times \mathbf{E}\,. \tag{3}$$

The condition $\left(G - \frac{1}{\gamma^2-1}\right) = 0$ can only be fulfilled for particles with $G > 0$, e.g. for protons with a momentum of $p_{\mathrm{magic}} = 0.7\mathrm{GeV}/c$. Using electric fields of the order of about 10 MV/m results in a ring of about 40 m radius.

Such an all-electric ring is proposed at Brookhaven National Laboratory (BNL) to measure the EDM of the proton [18].

2.2 Combined E and B fields

With a combined E/B ring it is possible to eliminate terms proportional to G if the condition

$$G\mathbf{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\mathbf{E} \times \mathbf{v} = 0$$

is fulfilled. This can be achieved for particles with arbitrary G. Such an all-in-one ring is under study by the JEDI (Jülich Electric Dipole moments Investigations) collaboration at Forschungszentrum Jülich [19].

2.3 Pure magnetic field

In a pure magnetic ring (i.e. $\mathbf{E} = 0$) eq. 2 reduces to

$$\mathbf{\Omega} = \frac{e\hbar}{mc}\left(G\mathbf{B} + \frac{1}{2}\eta \mathbf{v} \times \mathbf{B}\right)\,. \tag{4}$$

Here the build-up of an EDM effect is less obvious. The term proportional to G result in a spin precession in the horizontal plane of the storage ring. Due to this precession 50% of the time the projection of the spin vector is pointing parallel to the momentum vector and 50% anti-parallel. The electric field in

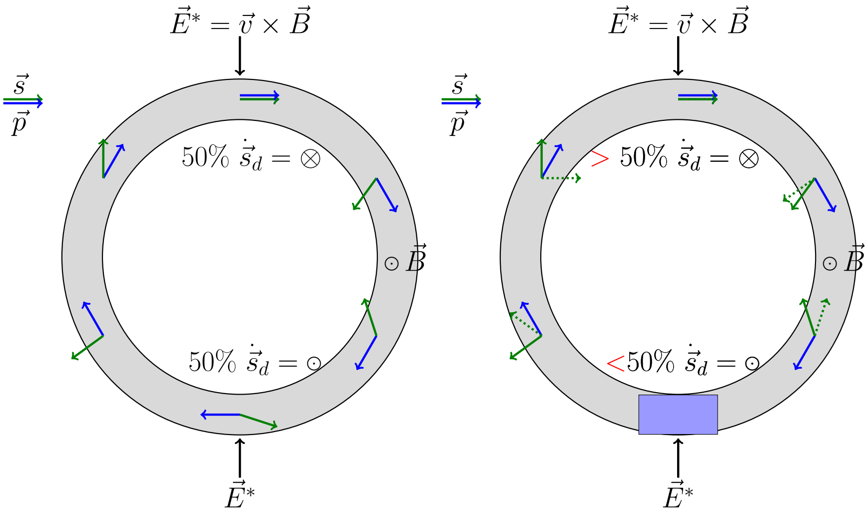

Fig. 2 Measurement of an EDM with a pure magnetic ring:
Left: In a pure magnetic ring particles feel a radial motional electric field $\mathbf{v} \times \mathbf{B}$. This causes a tilt of the spin vector due to an EDM out of the plane, e.g. in the upper hemisphere if the spin vector points parallel to the momentum vector and in the lower hemisphere if it points anti-parallel. This leads to an up-down movement of the spin vector due to an EDM and no vertical polarization will build up.
Right: A Wien-filter (blue box) will not affect the particle momentum (for the reference particle) but will influence the spin vector (dotted arrows) in such a way that it will point e.g. more than 50% parallel to the momentum vector. As a result a vertical polarization will build up due to an EDM.

the particle's rest frame caused by the laboratory magnetic field leads thus to an up-down movement of the spin due to the EDM. No vertical polarization will build up. Installing a resonant $\mathbf{E}/\mathbf{B}$ field combination with the condition $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$ at one or several places in the ring will have the following effect. The particle trajectory will not be affected ($\mathbf{E}^* = 0$) but the spin precession is perturbed ($\mathbf{B}^* \neq 0$) in such way that the symmetry between spin parallel and anti-parallel along the momentum vector is broken. If this so called "magic Wien filter" is operated at a correct resonance frequency given by $f_{\text{Wien}} = (k + \gamma G)\, f_{\text{rev}}$, k being an integer and f_{rev} the revolution frequency of the particles in the storage ring, a vertical polarization can build up and be measured as an EDM signal (see Fig. 2). Such an approach is under discussion at Forschungszentrum Jülich and could be performed at the existing (upgraded) storage ring COSY. A similar method using a radio-frequency radial electric field is discussed in [20].

2.4 Statistical and Systematic accuracy

The statistical accuracy of the measurement is given by

$$\sigma \approx \frac{b\hbar}{\sqrt{NfT\tau_p}PEA} \, . \quad (5)$$

b is a factor of the order of 1. Its exact value depends on the details of the injection and polarization measurement. The other variables are defined in Tab. 2. Taking the values given in Tab. 2 a statistical error of $10^{-29}e{\cdot}$cm per year can be reached for a dedicated ring (all-electric, all-in-one ring). For the pure magnetic ring where the EDM effect is only achieved with help of the resonant Wien-filter the sensitivity is of the order of $10^{-24}e{\cdot}$cm per year.

One major source of systematic error is a residual radial B field which mimics an EDM effect. If $\mu B_r \approx dE_r$, a radial magnetic field of $B_r = \frac{dE_r}{\mu_N} \approx 3 \cdot 10^{-17}$T causes the same effect as the EDM assuming $d = 10^{-29}e{\cdot}$cm in a field of $E = 10$MV/m. To fight such systematic errors the use of two beams running clock and counter-clockwise is proposed. A radial field B_r would result in a vertical separation of the two beams. For a more detailed discussion on systematic errors see [18, 21].

Many more tests and systematic studies are needed and are foreseen to reach the target numbers given in Tab. 2. In a first step using correction sextupoles the spin coherence time could already be increased from a few seconds to about 200 s in the COSY storage ring.

2.5 Comparison of the different methods

Tab. 3 lists the advantages and disadvantages of the three complementary approaches discussed. The first two approaches demand the construction of new dedicated storage rings. The third approach can be achieved on a much shorter time scale using the (upgraded) existing storage ring COSY.

variable	meaning	value
P	beam polarization	0.8
τ_p	Spin coherence time/s	1000
E	Electric field/MV/m	10
A	Analyzing Power	0.6
N	nb. of stored particles/cycle	4×10^7
f	detection efficiency	0.005
T	running time per year/s	10^7

Table 2 Typical values of parameters relevant for the statistical accuracy.

	advantage	disadvantage
1.) pure electric ring (BNL)	no **B** field needed	works only for p at fixed momentum
2.) combined ring (Jülich)	works for p, d, ^{3}He, ...	both **E** and **B** required
3.) pure magnetic ring (Jülich)	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity

Table 3 Comparison of the various methods discussed.

3 Summary & Outlook

EDMs of (charged) hadrons are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe. A step-wise approach to perform such measurements has been presented. After investigations of systematic errors at the existing COSY ring an upgraded COSY storage ring will be used to perform a first direct measurement of a charged hadron EDM. The next step will be the construction of dedicated storage rings at Forschungszentrum Jülich in Germany (all-in-one-ring for proton, deuteron and light nuclei) and Brookhaven National Laboratory in the USA (all-electric ring for proton) to reach for a higher sensitivity of $10^{-29} e\cdot$cm.

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