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# Charged Particle Electric Dipole Moment Searches in Storage Rings

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The Electric Dipole Moment (EDM) is a fundamental property of a particle, like mass, charge and magnetic moment. What makes this property in particular interesting is the fact that a fundamental particle with non-zero spin can only acquire an EDM via parity and time-reversal violating processes. EDM measurements contribute to the understanding of the matter over anti-matter dominance in the universe, a question closely related to the violation of these fundamental symmetries.

Up to now measurements of EDMs have concentrated on neutral particles. Charged particle EDMs can be measured using a storage ring as charged particle trap. Plans at the Forschungszentrum Jülich and the results of first test measurements at the COoler SYnchrotron COSY will be presented.

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## 1. Introduction

This document discusses first steps of the JEDI collaboration [1] towards a measurement of the Electric Dipole Moment (EDM) of charged particles in storage rings. EDMs of fundamental particles with spin violate parity $P$ and time-reversal $T$ ($\equiv CP$ via the $CPT$ theorem) symmetry. EDMs expected from the $CP$ violation of the SM lie between $10^{-33} and 10^{-31} e\,$cm for hadrons, orders of magnitude smaller than present experimental sensitivities. Many extensions of the SM predict EDMs in the range of $10^{-28} to 10^{-24} e\,$cm, in the reach of current and future experiments. For these reasons, EDMs are ideal candidates to search for physics beyond the Standard Model.

Up to now, measurements have concentrated on neutral particles (neutron, atoms, molecules). This is due to the fact that charged particles are accelerated in large electric fields and cannot be kept in small volumes like traps. As a consequence, storage rings have to be used to perform this kind of experiment.

This paper is organized as follows. Section 2 discusses spin motion in electric and magnetic fields. Section 3 describes the experimental setup at the COoler SYnchrotron COSY at Forschungszentrum Jülich. Section 4 presents the first results of test measurements.



## 2. Experimental Methods

The EDM can be measured by observing its influence on the spin motion of the particle. The starting point is the famous Thomas-BMT equation describing the influence of magnetic and electric fields on the the spin vector [2, 3, 4]:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{s}\times\left(\vec{\Omega}_{\mathrm{MDM}}+\vec{\Omega}_{\mathrm{EDM}}\right), \tag{2.1}$$

$$\vec{\Omega}_{\mathrm{MDM}} = \frac{q}{m}\left[G\vec{B}-\frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B})-\left(G-\frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{2.2}$$

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{\eta q}{2mc}\left[\vec{E}-\frac{\gamma}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{E}\right)+c\vec{\beta}\times\vec{B}\right]. \tag{2.3}$$

$\vec{s}$ denotes the spin vector in the particle rest frame in units of $\hbar$, $t$ is the time in the laboratory system and $\beta$ and $\gamma$ are the relativistic Lorentz factors. $q$ and $m$ are the charge and the mass of the particle, respectively. The magnetic and electric fields in the laboratory system are denoted by $\vec{B}$ and $\vec{E}$. The angular frequencies $\vec{\Omega}_{\mathrm{MDM}}$ and $\vec{\Omega}_{\mathrm{EDM}}$ are defined with respect to the momentum vector of the particle. The dimensionless parameters $G$ (gyromagnetic magnetic anomaly) and $\eta$ are related to the magnetic and electric dipole moments $\vec{\mu}$ and $\vec{d}$ according to [1]

$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{s} = (G+1)\frac{q\hbar}{m}\vec{s}, \tag{2.4}$$

$$\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s}. \tag{2.5}$$

[1] Note that here the $g$-factor is defined with respect to the magneton of the particle under consideration, $\frac{q\hbar}{2m}$, and not with respect to the nuclear magneton $\frac{q\hbar}{2m_{\mathrm{proton}}}$.

The dimensionless factor $\eta$ plays the same role for the EDM as $G$ does for the magnetic dipole moment (MDM). The main problem is that the relative strength of the EDM to the MDM is very small, the SM prediction is $\eta/G \approx 10^{-17}$. Having this in mind it is advisable to suppress contributions due to the MDM. Several options to measure the EDM in storage rings are presented in Ref. [5].

In this document we focus on the first test measurement at the pure magnetic storage ring COSY. With $\vec{E} = 0$ and neglecting field contributions parallel to the momentum vector, i.e $\vec{\beta} \cdot \vec{B} = 0$, the BMT-equation simplifies to

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{s} \times \vec{\Omega} \quad \text{with} \quad \vec{\Omega} = \frac{q}{m}\left(G\vec{B} + \frac{1}{2}\eta\vec{\beta} \times \vec{B}\right). \tag{2.6}$$

Since $\eta \ll G$, we ignore for the test measurements presented here the EDM contribution. This leaves one with a spin precession around the vertical axis (parallel to $\vec{B}$). It is convenient to relate this frequency to the cyclotron frequency $\omega_{\mathrm{cyc}} = q/(\gamma m)B$. The ratio

$$\nu_s = \frac{\Omega}{\omega_{\mathrm{cyc}}} = \gamma G \tag{2.7}$$

is called the spin tune.

## 3. Experimental Setup

The measurements presented here were performed at the COoler SYnchrotron COSY at the Forschungszentrum Jülich, Germany [6]. A vector polarized deuteron beam with a momentum of $p = 0.970\,\mathrm{GeV}/c$ was used [7]. The beam intensity was approximately $10^9$ deuterons per fill. An RF solenoid was operated to rotate the polarization by 90° degree from the initially vertical direction into the horizontal plane. Afterwards the beam was slowly extracted onto a carbon target, located at the edge of the beam, using a white noise electric field. Elastically scattered deuterons were detected in scintillation detectors consisting of rings around the beam pipe and bars running parallel to the beam. The active part of the detector covered a range from 9 to 13° in polar angle and was segmented into four regions in azimuthal angle (up, down, left and right). The elasticity of the event was guaranteed by stopping the deuterons in the outer scintillator ring and measuring their energy deposition in both scintillator layers. Roughly 5000 events/s at early times in the store were recorded. In brief, Tab. 1 lists the most important parameters of the experimental setup.

## 4. Recent results of test measurements

In this section selected results from recent measurements of the JEDI collaboration at the COoler SYnchrotron COSY are presented.

### 4.1 Spin coherence time (SCT)

Fig. 1 shows how the polarization vector can be manipulated with help of an rf-solenoid. Initially the polarization vector is pointing along the vertical $y$-direction, either upwards (red points) or downwards (black points) depending on the direction at injection. This is the stable spin axis

| | |
|---|---|
| COSY circumference | 183 m |
| deuteron momentum | 0.970 GeV/c |
| $\beta(\gamma)$ | 0.459 (1.126) |
| magnetic anomaly $G$ | $\approx -0.143$ |
| revolution frequency $f_{\rm rev}$ | 750603 Hz |
| cycle length | 150 to 400 s |
| duration of spin tune measurements | 90 s |
| event rate at $t=0$ | $5000\,{\rm s}^{-1}$ |

**Table 1:** Important parameters of the experimental setup.



in the accelerator. The upper plot shows the left-right asymmetry proportional to $P_y$, the lower plot shows the amplitude of the up-down asymmetry proportional to the polarization in the radial direction $P_x$. Because of the fast 120 kHz precession the lower plot shows only the amplitude of the polarization. With the help of the rf-solenoid the polarization vector is put into the horizontal plane (at $t \approx 95$ s). The left-right asymmetry goes to 0 and and an up-down asymmetry (lower plot) shows up. The polarization starts to precess. Due to decoherence, at the end of the cycle the polarization is lost.

A simple estimation shows that one expects without any correction spin coherence times of the order of one second. After bunching and cooling the momentum spread is $\Delta p/p = 10^{-5}$. This leads to a spread in the Lorentz $\gamma$-factor of $\Delta\gamma/\gamma = 2\cdot 10^{-6}$. The revolution period is $T \approx 10^{-6}$ s, keeping in mind that the spin tune is $\nu_s = \gamma G$, the naive expectation is that after about $10^6$, i.e. 1 s turns the spins decohere. The bunching cancels first order effects in $\Delta p/p$ and a SCT of a few seconds can be reached. With appropriate settings of the sextupole magnets, it is possible to cancel higher order decoherence effects. Details can be found in Refs. [8, 9]. Fig. 2 shows results from a setting where a SCT of over 1000 s was reached. The long SCT allows one to study the spin precession in the horizontal plane in more detail. This is subject of the next subsection.

### 4.2 Spin tune

Assuming no loss in polarization, the observed up-down asymmetry follows the following functional form

$$\begin{aligned} A_{up,dn}(t) &= AP\sin(\nu_s(t)\omega_{rev}t+\varphi) \\ &= AP\sin(\nu_s^0\omega_{rev}t+\varphi(t))\,, \end{aligned}$$

$P$ denotes the beam polarization and $A$ the analyzing power of the scattering process. The second line is just a reparameterization adapted for the analysis. Details of the analysis are outlined in Ref. [10]. Fig. 3 shows the $\varphi(t)$ as a function of time in the cycle for three different values of $\nu_s^0$, where $\nu_s^0$ is a first approximation to the spin tune. If the spin tune was constant and equal $\nu_s^0$, one would expect a constant $\varphi(t)$. If the spin tune was constant but different from $\nu_s^0$ a linear

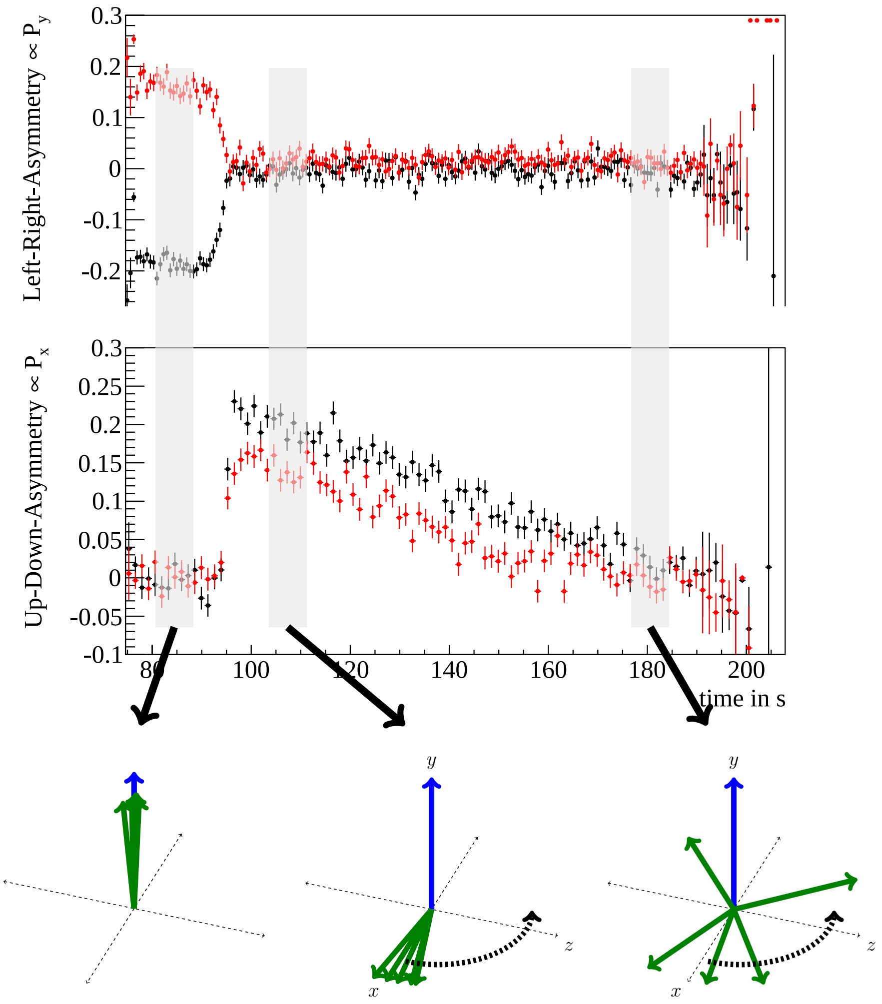


**Figure 1:** The left-right asymmetry (upper plot) and the amplitude of the up-down asymmetry (lower plot) as a function of time in cycle. Red points: cycle with initial polarization up, black points: cycle with initial polarization down. The diagrams illustrate the decoherence process.

dependence in $\varphi(t)$ would be observed. The difference of $\nu_s^0$ for the black and the blue curve is only $2 \cdot 10^{-9}$, indicating that the observation of the phase $\varphi$ vs. time is very sensitive to the spin tune. In general, the spin tune can be calculated from either of the three curves using the relation

$$|\nu_s(t)| = |\nu_s^0| + \frac{1}{\omega_{rev}} \frac{\mathrm{d}\varphi}{\mathrm{d}t} . \tag{4.1}$$

The value found, assuming a parabolic $\varphi(t)$, at time t=38 s is

$$|\nu_s(38\,\mathrm{s})| = (16\,097\,540\,628.3 \pm 9.7) \times 10^{-11}$$

i.e. the average spin tune can be determined with a precision of $\approx 10^{-10}$ in a single cycle, an accuracy never achieved before.

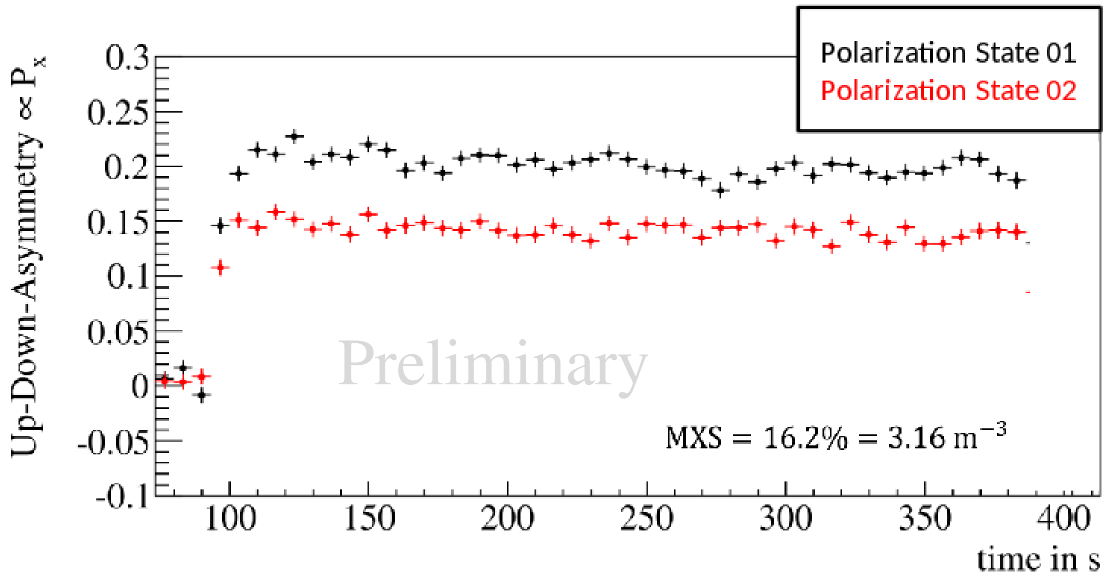


**Figure 2:** Amplitude of the up-down asymmetry for a cycle with a spin coherence time of over 1000 s for two different cycles (red: initial polarisation up, black: initial polarisation down)

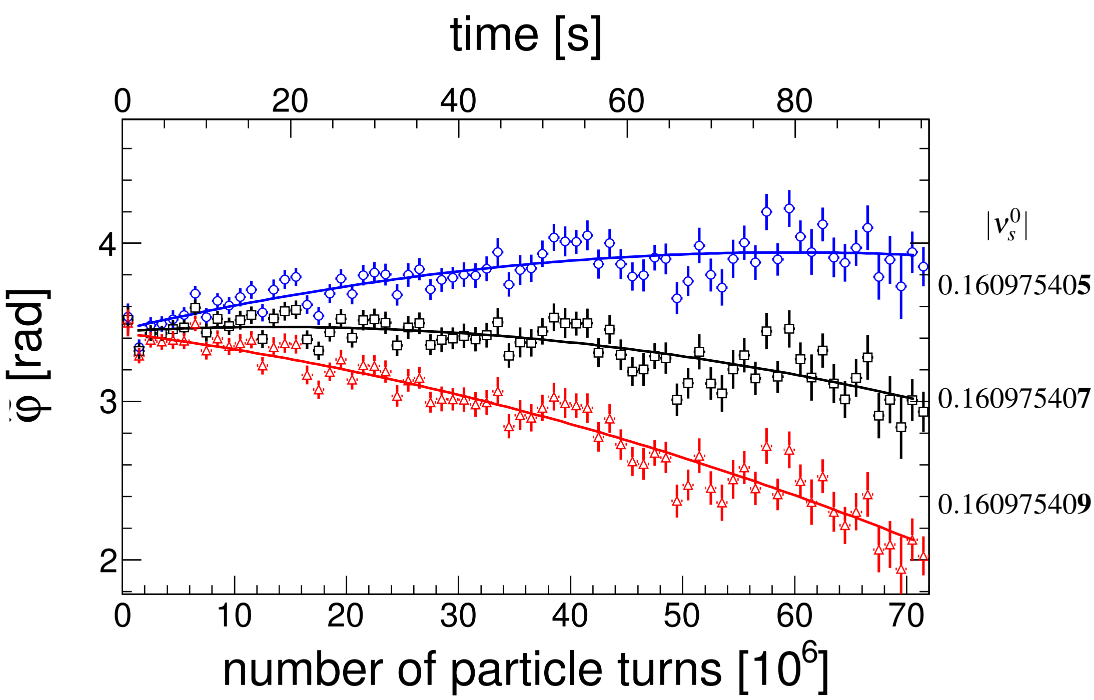


**Figure 3:** The phase advance $\varphi(t)$ as a function of time in cycle and number of particle turns for three different values of the the assumed spintune $\nu_s^0$. The diagrams illustrate the decoherence process.

## 5. Summary

Electric dipole moments are very sensitive probes to search for *CP*-violation beyond the Standard Model. EDMs of charged particle can be measured in storage rings. The first test measurements of the spin coherence time and spin tune performed at the Cooler Synchrotron COSY have been presented and show that spin precession can be observed with high accuracy in storage rings. This is one necessary condition for charged particle EDM measurements.

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