Measurement of Electric Dipole Moments at Storage Rings

Jörg Pretz
RWTH Aachen University & Forschungszentrum Jülich
on behalf of the JEDI collaboration

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Abstract

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 can only acquire an EDM via $\mathcal{P}$ and $\mathcal{T}$ 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 fundamental symmetries.

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

1 Introduction & Motivation

One of the great puzzles in particle physics is the matter – anti-matter asymmetry observed in the universe. In 1967 Sakharov showed that, starting form an equal amount of matter and anti-matter $\mathcal{P}$ and $\mathcal{CP}$ violating processes are necessary for baryogenesis [1]. The $\mathcal{CP}$ violation in the Standard Model (SM) is orders of magnitude too small to explain this effect. Therefore $\mathcal{CP}$ violating processes beyond the SM are searched for.

Electric Dipole Moments of fundamental particles violate $\mathcal{P}$ and $\mathcal{T}$ ($\equiv \mathcal{CP}$ via the $\mathcal{CPT}$ theorem). EDMs expected from the $\mathcal{CP}$ violation of the SM are between $10^{-33} - 10^{-31} e\,\text{cm}$ for hadrons, orders of magnitude smaller than experimental sensitivities. Many extensions of the SM predict EDMs in the range of $10^{-28} - 10^{-24} e\,\text{cm}$, in the reach of current and future experiments. For these reasons, EDMs are ideal candidates to search for physics beyond the SM.

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 operated to perform this kind of experiments.

The following section explains the principle of a charged particle EDM measurement at a storage ring. Section 3 describes the experimental setup at the COoler SYnchrotron COSY at Forschungszentrum Jülich. Section 4 presents first results of test measurements.

2 Experimental Method

The principle of the measurement is simple: For an elementary particle, the spin is the only vector defining a direction. A possible EDM has to be aligned along this axis. If an EDM exists, the spin vector will experience a torque in addition to the one caused be the magnetic moment. This torque results in change of the original spin direction. Finally, the spin direction can be determined by scattering the beam of a carbon target and analyzing the azimuthal distribution of the scattered particles. Although the measurement principle is simple, the smallness of the expected effect makes this a challenging experiment.

The spin motion of a particle in electric and magnetic fields is governed by the Thomas-BMT equation [2]:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{s} \times \left(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}\right) , \tag{1}$$

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

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{\eta q}{2mc}\left[\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{E}\right) + c\vec{\beta}\times\vec{B}\right] . \tag{3}$$

$\vec{s}$ denotes the spin vector in the particle rest frame in units of $\hbar$, t is the time in the laboratory system, β and γ are the relativistic Lorentz factors. q and m are the charge and the mass of the particle, respectively. The magnetic and electric field 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 (magnetic anomaly) and η are related to the magnetic and electric dipole moments $\vec{\mu}$ and $\vec{d}$ according to [1]

$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{s} = (G+1)\frac{q\hbar}{m}\vec{s}, \tag{4}$$

$$\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s}. \tag{5}$$

Taking Eq. (1) as a starting point, different approaches are possible. Using a ring with only electric fields ($\vec{B}=0$), a combined ring with electric and magnetic fields or a pure magnetic ring ($\vec{E}=0$). Eliminating terms proportional to G is

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

advisable, because spin motions caused by the magnetic moment are in general much larger than those caused by the EDM. Note that for hadrons $|G|$ is of order one, whereas η is approximately $2 \cdot 10^{-10}$ for an EDM of $d \approx 10^{-24} e\,\mathrm{cm}$. More details about the various options are discussed in Ref. [3, 4].

This document focuses on measurements at the magnetic ring COSY. In a pure magnetic ring (i.e. $\vec{E} = 0$) Eq. (1) reduces to

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{s} \times \vec{\Omega} \quad \text{with} \quad \vec{\Omega} = \frac{q}{m}\left(G\vec{B} + \frac{1}{2}\eta\vec{\beta} \times \vec{B}\right) . \tag{6}$$

The term proportional to $\vec{\beta} \cdot \vec{B}$ has been omitted in Eq. (6). In this method the EDM couples to the motional electric field $\vec{\beta} \times \vec{B}$. The term proportional to G results in a spin precession in the horizontal plane of the storage ring. For an EDM measurement the effect of this precession can be suppressed by using radio-frequency (RF) E and/or B fields [4, 5, 6].

For test measurements, the EDM effect is neglected. The precession frequency simplifies to

$$\vec{\Omega} = \frac{q}{m} G\vec{B} \,. \tag{7}$$

Dividing Ω by the cyclotron frequency $\omega_{\mathrm{cyc}} = \frac{q}{m\gamma} B$ leads to the so called spin tune

$$\nu_s = \frac{\Omega}{\omega_{\mathrm{cyc}}} = \gamma G \,.$$

It is given as the number of spin revolutions relative to the momentum vector per particle turn around the invariant spin axis. The aim of the test measurements was to measure the spin tune and use it as a tool to study systematic effects.

3 Experimental Setup

The measurements presented here were performed at the COoler SYnchrotron COSY at the Forschungszentrum Jülich, Germany [7]. COSY provides polarized proton and deuteron beams in the momentum range 0.3 to 3.7 GeV/c. For the results presented here a vector polarized deuteron beam with a momentum of $p = 0.970\,\mathrm{GeV}/c$ was used [8]. The beam intensity was approximately 10^9 deuterons per fill. An RF solenoid was used to rotate the spin by 90 degree from the initially vertical direction into the horizontal plane. Afterwards the beam was slowly extracted onto a carbon target using a white noise electric field. Elastically scattered deuterons were detected in scintillation detectors consisting of rings and bars around the beam pipe. The detector covers a range from 9 to 20 degrees in polar angle and is segmented in four regions in the 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. Roughly 5000 events/s were recorded. In brief, Tab. 1 lists the most important parameters of the experimental setup.

COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency $f_{\rm rev}$	752543 Hz
cycle length	150 s
duration of spin tune measurements	90 s

Table 1: Important parameters of the experimental setup.

4 Analysis and Results of Spin Tune Measurements

For the experimental setup described above the spin tune is $\nu_s = \gamma G \approx -0.16$. At a revolution frequency of $f_{\rm rev} \approx 753\,$kHz this leads to a spin precession frequency of $f_{\rm spin} = |\nu_s| f_{\rm rev} \approx 120$ kHz. The spin precession frequency can be detected via the modulation in the counting rate in the lower and upper detector:

$$N_{\rm up,dn} = I a \bar{\sigma} (1 \pm \frac{3}{2} P \overline{A_y} \cos(2\pi f_{\rm spin} t + \varphi)) \,.$$

P and $\overline{A_y}$ denote the polarization and the analyzing power averaged over the detector acceptance. Their approximate values are $|P| \approx 0.45$ and $\overline{A_y} \approx 0.46$. $\bar{\sigma}$ is the unpolarized acceptance weighted cross section. Combining the counting rates of the upper and lower detector allows one to determine $|\nu_s| = f_{\rm spin}/f_{\rm rev}$. The result is to first order independent of quantities like beam flux, I, and detector acceptance and efficiencies, a. The main difficulty in the analysis is the fact that the spin revolution frequency $f_{\rm spin}$ is large compared to the detected event rate of approximately 5000 events/s. On average only every 24th oscillation period an event is recorded. This requires a special algorithm described in detail in Ref. [9].

The spin precession was observed over a time period of about 90 s. This time is limited by the length of the accelerator cycle and the spin coherence time. Figure 1 shows the result. The upper part of Fig. 1 depicts the spin tune as a function of time in one cycle. A spin tune value is obtained for every 2 s time interval. The statistical error on a frequency measurement is given by $\sigma_f = \sqrt{6/N} 2/(3\pi P \overline{A_y} T)$ where T is the time interval in which N events are recorded evenly over time. With $3/2\, P\overline{A_y} \approx 0.3$ and $N \approx 5000/\text{s} \times 2\,\text{s}$ a statistical error of $\sigma_{\nu_s} = \sigma_f / f_{\rm spin} \nu_s = 2 \cdot 10^{-8}$ is reached as can be seen in Fig. 1. At later times the error increases, because spin decoherence leads to a decrease of P. How to maintain a large P over time, i.e to obtain a large spin coherence time, is described in Ref. [10].

Performing a global analysis over a $T = 90\,$s time interval assuming a linear spin dependence vs. time, a smaller error can be achieved. This leads to the

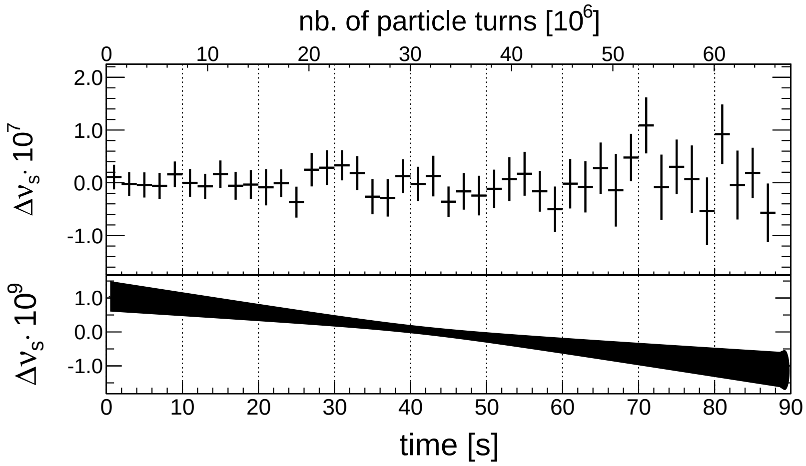

Figure 1: Spin tune as a function of time for one cycle. Upper plot: Spin tune determined in every 2 s time interval making no assumption about spin tune changes vs. time Lower plot: Spin tune determined over the whole cycle assuming a linear spin tune change over time.

result shown in the lower plot of Fig. 1. The error band, indicating the statistical error, is smallest at about 40 s where the spin tune can be determined with a statistical precision of 10^{-10}.

The result presents the most precise spin tune measurement at a storage ring. As mentioned above, the observation of spin precision is the tool to get access to fundamental quantities like G and d. The spin precision observed here is completely driven by G and ring imperfections. These imperfections cause the spin tune ν_s to deviate form the value γG. An EDM alone of $d = 5 \cdot 10^{-23} e{\cdot}\mathrm{cm}$ would cause a $\nu_{s,d} = \eta\beta\gamma/2 = 5 \cdot 10^{-11}$. This measurement proves that statistically one is able to observe such tiny spin precessions. Presently, this spin tune measurement serves as a tool to study systematic effects. For example, spin tune changes predicted by simulations as function of magnet settings in COSY can be compared to the measurements and help to validate the simulations.

5 Summary and Conclusions

Charged particle electric dipole moments can be measured at storage rings by observing their spin precession. First test measurements at the Cooler Synchrotron COSY were performed. The spin tune was measured with a relative precision of $10^{-10}/0.16 = 6 \cdot 10^{-10}$ in a 90 s time interval. These measurements provide an important tool to study systematic effects for future EDM measurements at storage rings.

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