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The Search for Electric Dipole Moments of Charged Particles Using Storage Rings

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One of the major problems of modern particle physics is the inability of the Standard Model (SM) of Particle Physics to explain the matter-antimatter asymmetry in the Universe. Therefore, the pursuit of physics beyond the SM is required and one of the necessary conditions for the appearance of the matter-antimatter asymmetry is the violation of the CP symmetry. Permanent electric dipole moments (EDMs) of particles violate CP symmetry, so EDM measurements of fundamental particles are able to probe new sources of CP-violation.
Storage rings make it possible to measure EDMs of charged particles by observing the effect of the EDM on the spin motion in the ring. The Cooler Synchrotron COSY at the Forschungszentrum Julich provides polarized protons and deuterons with momenta up to 3.7 GeV/s, which is an ideal testing ground and starting point for the JEDI collaboration (Jülich Electric Dipole moment Investigations) for such an experimental program.
The preliminary results of the first direct (precursor) measurements of the deuteron EDM in COSY are presented. This is the first stage of the experimental program to determine the EDMs of proton and deuteron using storage rings [1], [2].

KEYWORDS: electric dipole moment, baryon asymmetry, CP symmetry violation

1. Introduction

The Standard Cosmological Model (SCM) fails to explain the baryon asymmetry level in the Universe. The rate of baryon asymmetry is expressed as $\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$, where n_b and $n_{\bar{b}}$ are the numbers of baryons and antibaryons and n_γ is the number of relict photons. According to the SCM $\eta \sim 10^{-18}$ [3] while the experimental observations yield η of the oder of 10^{-10} [4], [5]. The conditions for baryogenesis in the Universe were formulated by Andrei Sakharov in 1967, and one of them states that C and CP invariances must be violated [6]. Electric dipole moments (EDMs) of particles violate both parity (P) and time reversal symmetry (T) which means that, if CPT symmetry is conserved, it also violates CP symmetry. Therefore, finding the EDM of a fundamental particle would allow us to understand the baryogenesis of the Universe.

2. Spin motion in a storage ring

The spin vector $\vec{S}$ motion in a storage ring with radial electric $\vec{E}$ and vertical magnetic field $\vec{B}$ in the rest frame of the particle is described by the Thomas-BMT equation [7], [8],

$$\frac{d\vec{S}}{dt} = [\,\vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{cyc}} + \vec{\Omega}_{\mathrm{EDM}}] \times \vec{S}, \tag{1}$$

where angular velocities consists of two parts, acting through magnetic dipole moment (MDM) and EDM,

$$\begin{aligned} \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} &= -\frac{q}{m}(G\vec{B} - (G - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} \times \vec{E}}{c}), \\ \vec{\Omega}_{\text{EDM}} &= -\frac{\eta_{\text{EDM}} q}{2mc}(\vec{E} + c\vec{\beta} \times \vec{B}). \end{aligned} \tag{2}$$

Here G is the anomalous gyromagnetic g-factor and η_{EDM} denotes the electric dipole factor. The case of $\vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} = 0$ is called a "frozen spin" condition because in the absence of EDM spin stays aligned to the momentum of the particle. The "frozen spin" condition in a purely electric ring can be reached for particles with $G > 0$ if $(G - \frac{1}{\gamma^2-1}) = 0$. In this case the EDM would be sensed by the radial electric field and spin will precess around the radial axis leading to a vertical spin component.

3. Proof of principle EDM experiment at COSY

3.1 Magnetic storage ring COSY

The JEDI collaboration aims to measure the charged hadron's EDM using a stepwise approach and, as the first step, the precursor experiment was done at the COoler SYnchrotron COSY at Forschungszentrum Jülich [1]. A pure magnetic storage ring COSY has been previously used for hadron physics experiments and is capable of providing polarized protons and deuterons at momenta from $p = 0.3$ to 3.7 GeV/c. It is an ideal starting point for the proof-of-principal for the search of the charged hadron EDM. The schematic layout of COSY and principal elements are shown on Fig.1.

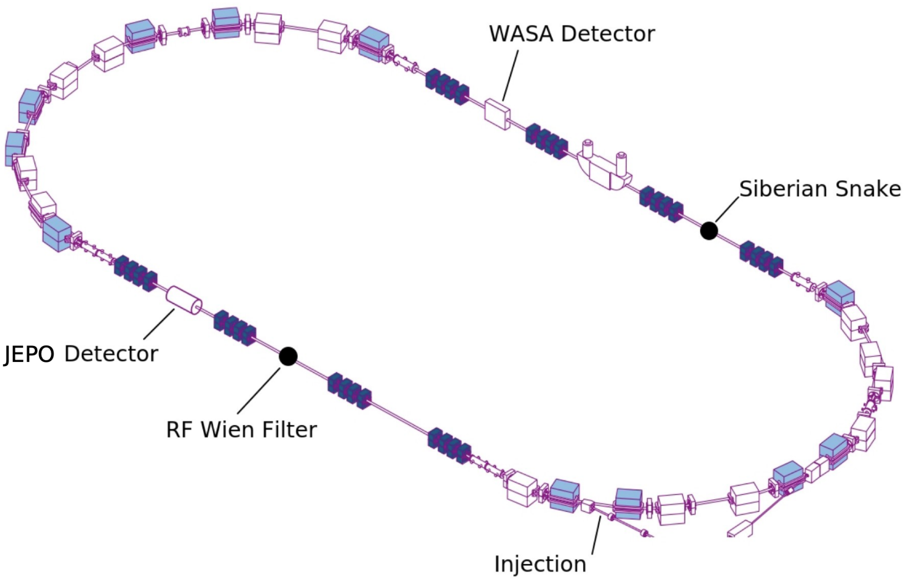

Fig. 1. The schematic of COSY showing the positions of the principal elements.

3.2 Experimental layout

Vertically polarized deuterons were injected into the COSY ring and accelerated to a momentum of 970 MeV/c. After the bunching and the electron cooling, the beam was extracted on a carbon block

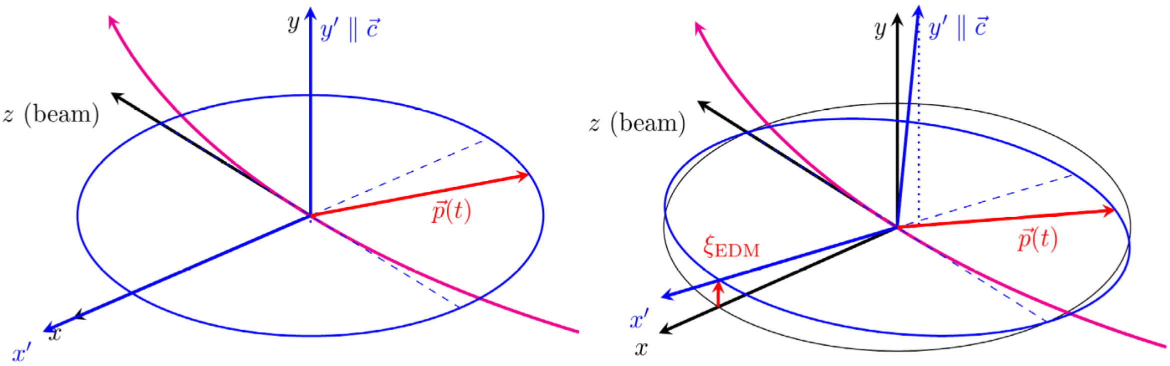

Fig. 2. Invariant spin axis is vertical in case of an ideal ring in the absence of the EDM (left) and tilted in radial direction due to EDM effect (right).

target and elastically scattered deuterons were detected with a WASA polarimeter. Then spins of the particles were rotated into the horizontal plane with an RF solenoid. Optimisation of the decoherence of the in-plane polarization time was done using sextupole magnets [10], [11] and a long spin coherence time of about 1000 s. was reached for the purposes of the experiment.

In a purely magnetic ring, according to the Eq. 2, spin rotation caused by the EDM receives a contribution in the vertical direction from the motional electric field ($c\vec{\beta} \times \vec{B}$). However, due to the spin precession around $\vec{B}$, there will be tiny oscillations of the vertical polarization and no build-up accumulation. In order to overcome this obstacle RF Wien filter was used [9], [2], it was operated on one of the harmonics of the spin precession frequency (871 kHz) and the phase-lock feedback was used to keep the relative phase between the spin precession and the Wien filter RF oscillations constant throughout the measurements [12], [13]. That leads to a particle receiving a spin kick in the same direction for each turn it passes through the RF Wien filter, resulting in a polarization build-up.

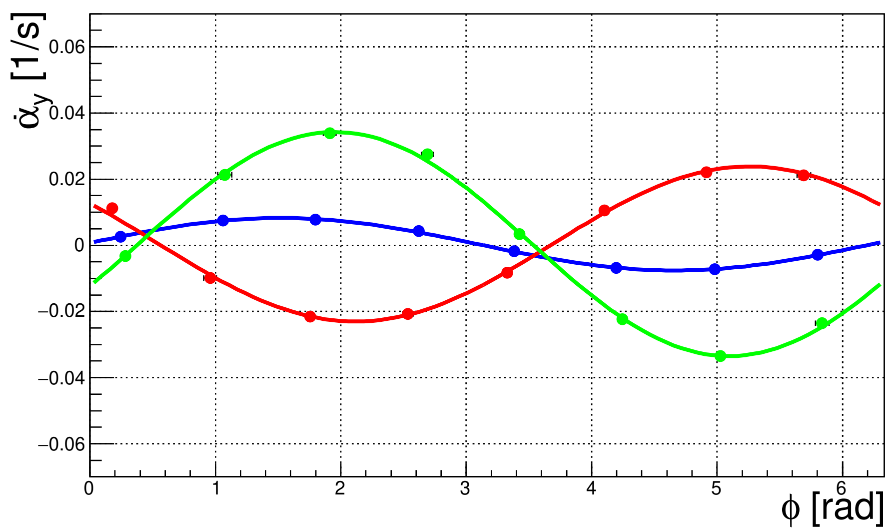

Fig. 3. Out-of-plane rotation angle $\dot{\alpha}$ as function of the relative phase between spin precession and Wien filter RF. Wien filter rotation $\phi^{\mathrm{WF}} = 0$ mrad, snake χ^{sol} is set to -26.17 mrad (red), 0 mrad (blue) and 26.17 mrad (green).

3.3 Invariant spin axis determination

In the ideal ring and in the absence of the EDM, the invariant spin axis, about which the spin of the particle oscillates, is vertical (direction of the $\vec{B}$ field), Fig.2. The EDM produces the oscillation of the vertical spin component, this results in a tilt of the invariant spin axis away from the vertical into radial direction, Fig.2. In reality, however, there are additional magnetic misalignments, which is why the invariant spin axis is inclined further. The direction of the invariant spin axis provides an experimental access to the EDM.

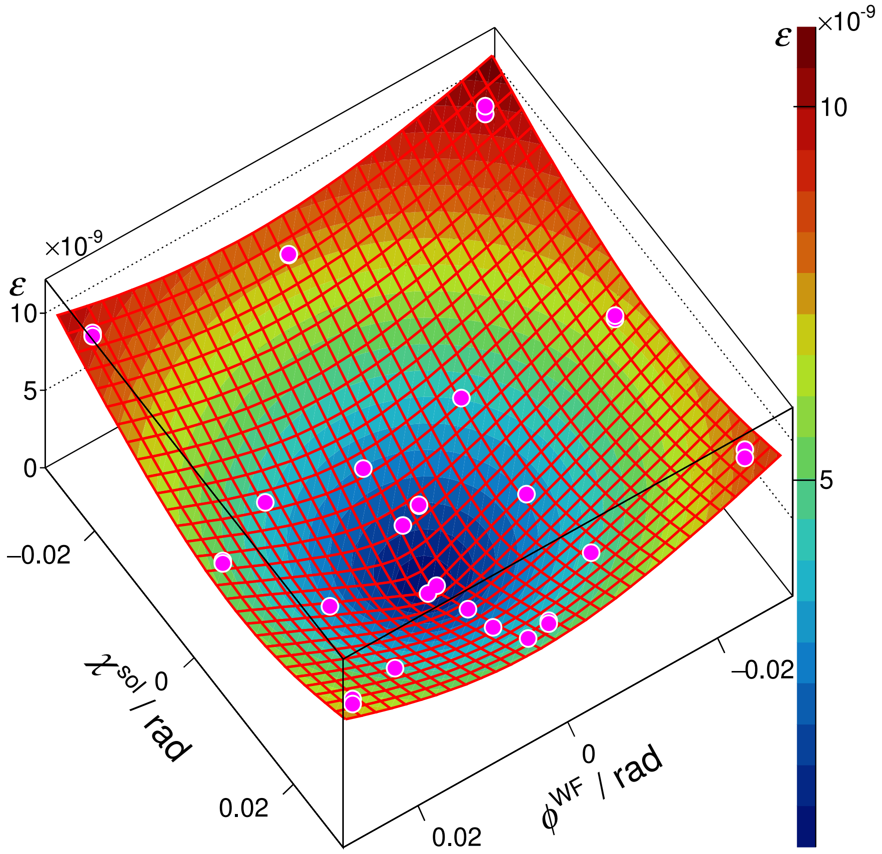

Fig. 4. The map of the resonance strength ε^{EDM} for various Wien filter angle ϕ^{WF} and Sibirian snake spin rotation angle χ^{sol}.

Measurements were performed for several rotation angles around the beam direction of the RF Wien filter (ϕ^{WF}) and for several Sibirian snake currents (χ^{sol}) on the opposite side of the ring, to rotate the invariant spin axis in the longitudinal direction. The EDM resonance strength $\varepsilon^{\mathrm{EDM}}$ can be defined as

$$\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}, \qquad (3)$$

where Ω^{p_y} denotes spin angular frequency and Ω^{rev} denotes the revolution frequency. Taking into account that the EDM induced vertical polarization oscillations can be written as

$$p_y(t) = asin(\Omega^{p_y} t + \phi_{\text{RF}}), \tag{4}$$

one can show that ε^{EDM} can be determined as

$$\varepsilon^{\text{EDM}} = \frac{\dot{\alpha(t)}|_{t=0}}{acos(\phi_{\text{RF}})} \cdot \frac{1}{\Omega^{\text{rev}}}, \tag{5}$$

where $\dot{\alpha(t)}|_{t=0}$ denotes the initial slope of the out-of-plane polarization rotation angle.

The out-of-plane angles $\dot{\alpha}$ were observed for 8 relative phases between spin precession and the RF Wien filter, resulting in the sinusoidal dependencies, shown in Fig.3. The decoherence of the horizontal polarization [14] was distinguished by simultaneously fitting the time dependencies for full polarizations and slopes of the vertical polarization build-up. An example of the resulting map for the resonance strength versus Wien filter and snake angles is shown in Fig.4. The minimum of the fitting surface determines the orientation of the invariant spin axis, which yields $(\phi_0^{\text{WF}}, \chi_0^{\text{sol}}) = (3.6, 5.4)$ mrad. The spin tracking calculations are required to determine invariant spin axis of the ring, accounting for all misalignments.

References

[1] F. Abusaif *et al.*, *Storage Ring Search for Electric Dipole Moments of Charged Particles - Feasibility Study*, CERN Yellow Report **257** (2021), https://doi.org/10.23731/CYRM-2021-003.
[2] F. Rathmann, N.N. Nikolaev, J. Slim, Phys. Rev. Accel. Beams **23** 024601 (2020).
[3] W. Bernreuther, Lect. Notes Phys. **591** 237 (2002).
[4] WMAP collaboration, Astrophys. J. Suppl. **148** 1 (2003).
[5] V. Barger, J. P. Kneller, H.-S. Lee, D. Marfatia and G. Steigman, Phys. Lett. **B566** 8 (2003).
[6] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** 32 (1967).
[7] T. Fukuyama and A. J. Silinko, Int. J. Mod. Phys. **A28** 1350147 (2013).
[8] A. Saleev *et al.*, Phys. Rev. ST Accel. Beams **20** 072801 (2017).
[9] J. Slim *et al.*, Nucl. Instrum. Methods Phys. Res. A **828** 166 (2016).
[10] Z. Bagdasarian, S. Bertelli, D. Chiladze, Phys. Rev. ST Accel. Beams **17** 052803 (2014).
[11] G. Guidoboni *et al.*, Phys. Rev. Lett. **117** 054801 (2016).
[12] N. Hempelmann *et al.*, Phys. Rev. Lett. **119** 014801 (2017).
[13] N. Hempelmann *et al.*, Phys. Rev. Accel. Beams **21** 042002 (2018).
[14] N. Hempelmann, PhD Thesis (2018).