PROCEEDINGS OF SCIENCE

PoS(PSTP2022)035

The search for electric dipole moments of charged particles using storage rings

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Vera Shmakova[a,*] **for the JEDI collaboration**

[a] *GSI Helmholtzzentrum für Schwerionenforschung GmbH,*
Planckstraße 1, 64291 Darmstadt, Germany

E-mail: `v.shmakova@fz-juelich.de`

The Standard Model (SM) of Particle Physics cannot explain the matter-antimatter asymmetry in the Universe. Especially, new sources of CP-violation are necessary, and this is why physics beyond the ST is being explored. The search for permanent Electric Dipole Moments (EDMs) of elementary particles has the potential to provide a powerful tool to probe such new sources of CP-violation. Finding an EDM would be a convincing indication for physics beyond the SM. 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 Jülich provides polarized protons and deuterons with momenta up to 3.7 GeV/s and it constitutes an ideal testing ground and starting point for such an experimental program to search for EDMs of charged particles. This report provides an overview of the current status of the JEDI project for the first direct measurement of the deuteron EDM at COSY. The analysis is currently ongoing. Due to the complexity of storage rings, this study combines high precision measurements and thorough understanding of the systematic uncertainties involved.

Workshop on Polarized Sources Targets and Polarimetry 2022 (PSTP22),
26-30 September 2022
Mainz, Germany

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[*] Speaker

1. Introduction

The Standard Cosmological Model (SCM) does not explain the baryon asymmetry in the Universe, which is quantified by the ratio of baryon to photon number densities, $\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$, where n_b and $n_{\bar{b}}$ are the numbers of baryons and antibaryons and n_γ is the number of relic photons. The SCM predicts that $\eta \sim 10^{-18}$ [3], but experimental observations reveal a much higher value of η of the order of 10^{-10} [4], [5]. In 1967, Andrei Sakharov proposed a set of requirements that are necessary for baryon-antibaryon asymmetry to occur in the Universe, one of which is the violation of both C and CP invariance [6].

Electric dipole moments (EDMs) of particles violate both parity (P) and time reversal symmetry (T). This implies that if CPT symmetry is conserved, CP symmetry is also violated. Thus, detecting the EDM of a fundamental particle can provide valuable insights into the matter-antimatter asymmetry in the Universe.

The JEDI collaboration is working towards measuring the EDMs of charged hadrons using a storage ring. An overview of the existing limits of electric dipole moments of various particles is shown in Fig. 1. Currently, there is no direct measurement of the proton EDM, the limit for the proton EDM was derived based on the EDM measurement of the mercury atom, and there exist no limits at all for the deuteron EDM.

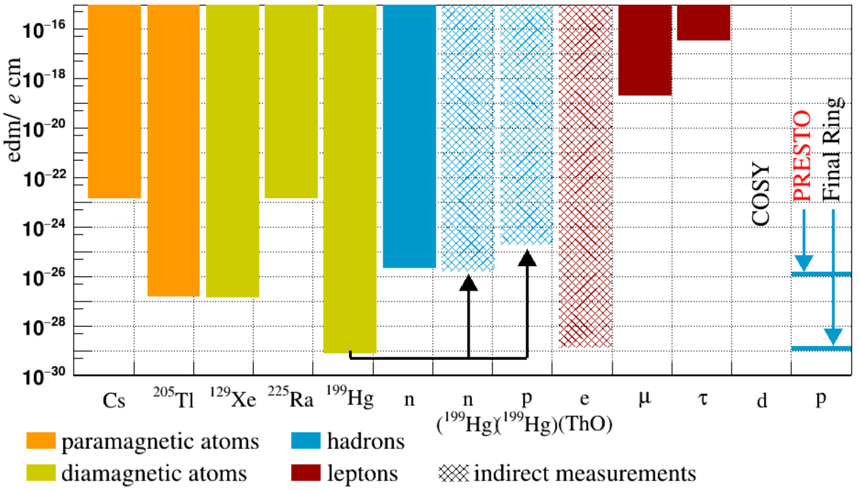

Figure 1: Existing limits for electric dipole moment for various particles (figure taken from [1]). The last two columns are showing the goals of the JEDI collaboration. The initial stage with a magnetic ring COSY is aiming at the first measurement of the deuteron EDM. The goal limits for the second stage "PRESTO" and for the third stage with the final ring are shown in the last column. The last two stages are described in more detail in Section 3.

2. Measurement of the EDM using storage rings

The motion of the spin vector $\vec{S}$ in a storage ring with respect to the cyclotron motion, subject to a radial electric field $\vec{E}$ and a vertical magnetic field $\vec{B}$, is described by the Thomas-BMT equation [7], [8], [9]

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

The spin precession depends on the angular velocities due to the magnetic dipole moment (MDM) and the electric dipole moment (EDM), $\vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{cyc}}$ and $\vec{\Omega}_{\mathrm{EDM}}$, given by

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

Here G is the anomalous gyromagnetic g-factor and η_{EDM} denotes a dimensionless electric dipole moment factor, while the electric dipole moment $\vec{d} = \eta_{\mathrm{EDM}}\frac{q}{2mc}\vec{S}$. When the spin of a particle remains aligned with its momentum in the absence of an EDM, this is referred to as the "frozen spin" condition. This condition arises when the term $\vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{cyc}}$ vanishes. For particles with $G > 0$, the frozen spin condition can be achieved in a purely electric ring if the momentum of the particle satisfies the condition $(G - \frac{1}{\gamma^2-1}) = 0$. In this case the radial electric field $\vec{E}$ will exert a torque $\vec{d}\times\vec{E}$, and the spin will precess around the radial axis in the ring leading to a vertical spin component in the beam. This is the idea behind the final stage of the JEDI project, making use of a dedicated purely electric ring to achieve the necessary precision for the proton EDM measurement of up to $10^{-29}\mathrm{e}\cdot\mathrm{cm}$ (see last column of Fig. 1) [1]. Meanwhile, as the first stage, a proof-of-principle experiment is currently underway with the existing magnetic storage ring COSY in Jülich, Germany [1], depicted in Fig. 2.

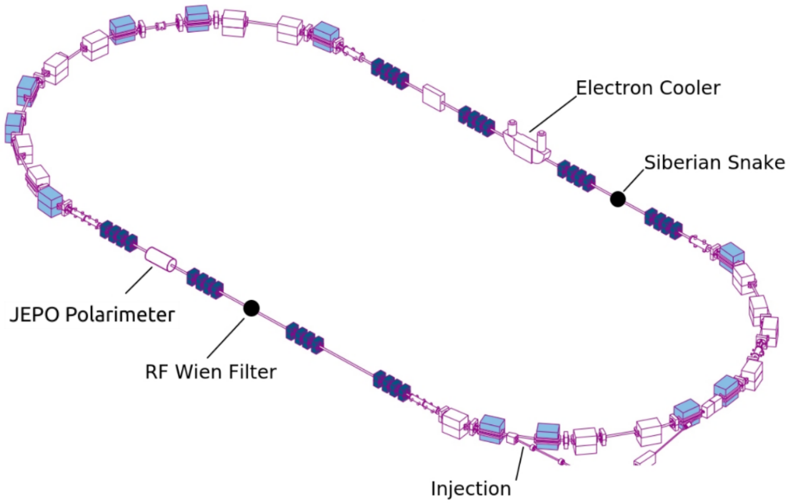

Figure 2: The schematic of COSY showing the positions of the principal elements.

2.1 EDM experiment at COSY

The magnetic storage ring COSY has been previously used for hadron physics experiments and is capable of providing polarized protons and deuterons at momenta up to 3.7 GeV/c. It is an ideal starting point for the search of the EDMs of charged hadrons. The schematic layout of COSY and principal elements are shown in Fig. 2. The experiment was carried out with vertically polarized deuterons injected into the COSY ring and accelerated to a momentum of 970 MeV/c. The principal values for the deuteron EDM experiment at COSY were $G_\mathrm{d} = -0.143$, $\beta = 0.4594$ (see Eq. 2). An EDM of $d = 10^{-26}$ e $\cdot$ cm corresponds to $\eta_\mathrm{EDM} = 1.9 \cdot 10^{-12}$. After bunching and electron cooling, the beam was extracted on a carbon block target and the elastically scattered deuterons were detected with the JEPO polarimeter [12]. Subsequently, the spins of the particles were rotated into the horizontal plane by means of an radio-frequency (RF) solenoid. The spin coherence time of the in-plane polarization was optimized using sextupole magnets [13], [14]. About 1000 s was reached for the purposes of the experiment.

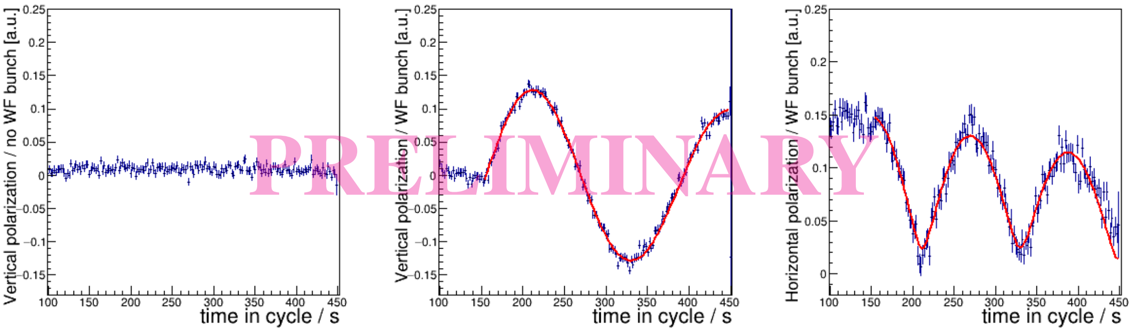

Figure 3: Example of a dataset obtained for one cycle for $\phi^{\mathrm{WF}} = -2°$, $\chi^{\mathrm{sol}} = -4°$. Left: vertical polarization for the bunch shielded from the Wien filter field, staying constant during the cycle. Center and right: combined fit for the vertical and in-plane polarization.

In a purely magnetic ring, according to Eq. (2), the spin rotation caused by the EDM receives a contribution in the vertical direction from the motional electric field $\vec{E}_r = c\vec{\beta} \times \vec{B}_y$. Due to the spin precession caused by the term $G\vec{B}$, in the absence of a static electrical $\vec{E}$ field, there will be only tiny oscillations of the vertical polarization. In order to accumulate the EDM signal, an RF Wien filter was used [2], [11]. It provides exactly orthogonal magnetic and electric fields and was operated on one of the harmonics K of the spin precession frequency $f_s = f_\mathrm{rev} \cdot \gamma G$, so that the Wien filter is operated at $f_\mathrm{WF} = f_\mathrm{rev}\,|K + \gamma G|$, i.e., for deuterons at $K = -1$ and $f_\mathrm{rev} \sim 750$ kHz, $f_\mathrm{WF} \sim 871$ kHz.

A real-time feedback system was used to monitor the spin tune ν_s [15] and to keep the Wien filter frequency at $f_\mathrm{WF} = f_\mathrm{rev}(K + \nu_s)$ by maintaining the relative phase between spin precession and Wien filter RF oscillations constant throughout the measurements [16], [17]. With such a setting a particle receives a spin kick in the same direction for each turn it passes through the RF Wien filter, resulting in a out-of-plane accumulation of the vertical polarization P_y.

In addition, the Wien filter was equipped with fast switches that are capable of turning the RF of the Wien filter on and off for each of several bunches in the ring, allowing us to manipulate the polarization of one chosen bunch in the ring. This way, having two bunches in the machine, one of the bunches can be shielded from the Wien filter field (Fig. 3, left) and be used to lock the phase and fulfill $f_\mathrm{WF} = f_\mathrm{rev}K + f_s$ with the feedback system, while the other bunch experiences the full field of the Wien filter, and its effect on P_y and P_x can be measured (Fig. 3, center and right).

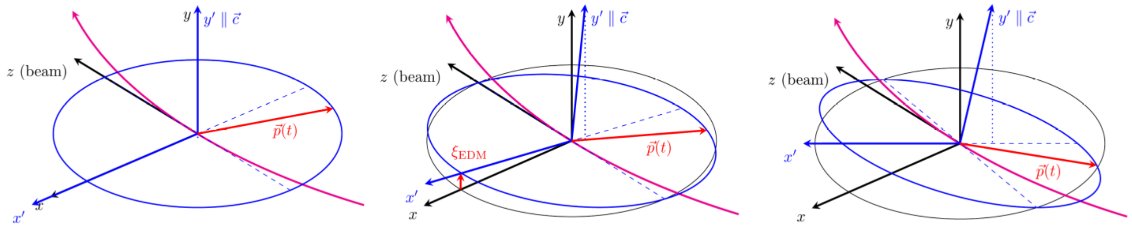

Figure 4: The invariant spin axis is vertical in case of an ideal ring in the absence of the EDM (left), tilted in radial direction due to EDM effect (center) and tilted further in both radial and longitudinal directions due to magnetic misalignments (right).

2.2 Determination of the invariant spin axis orientation

The observable that we are aiming to measure is the so-called invariant spin axis, an axis about which the spin of the particle is precessing at a given point of the orbit. In the absence of the EDM, this axis coincides with the direction of the magnetic bending field of the ring dipoles $\vec{B}_y$ in an ideal ring, i.e., it is precisely vertical, as shown on Fig. 4, left. As soon as the EDM or magnetic imperfections enter the picture, these will cause a tilt of the invariant spin axis away from the vertical direction. An EDM in an ideal ring will lead to a radial tilt of the invariant spin axis (see Fig. 4, center). In reality, magnetic misalignments will tilt the axis in both directions away from the vertical axis (see Fig. 4, right). Once the impact of magnetic imperfections is known, the direction of the invariant spin axis provides an experimental access to the EDM. As soon as the magnetic field axis of the Wien filter is parallel to the invariant spin axis, there would be no polarization build-up observed. Therefore, the way to measure the orientation of the invariant spin axis in the experiment is to tilt to various angles either the $\vec{B}$ field of the RF Wien filter, or the invariant spin axis itself by making use of a snake on opposite side of the ring (see Fig. 2). This way one can search for the combination of ϕ^{WF} and χ^{sol} for which no out-of-plane rotation of the polarization is detected. For this purpose the Wien filter was rotated around the beam direction, providing a radial tilt of ϕ^{WF} in the range $\pm 4^\circ$ and the snake was used to incline the invariant spin axis at the location of the Wien filter by χ^{sol} in longitudinal direction.

The resonance strength ε can be defined as ratio between spin angular frequency Ω^{p_y} and the revolution frequency Ω^{rev}:

$$\varepsilon = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}. \tag{3}$$

During the experiment, data for both vertical and horizontal asymmetries were collected and simultaneous fits of both datasets (shown on Fig. 3) enables a more accurate determination of the oscillation frequency. A preliminary map of the resulting resonance strengths ε for various Wien filter rotations ϕ^{WF} and the solenoid settings χ^{sol} is shown on Fig. 5. The minimum of the surface indicates the orientation of the invariant spin axis at the location of the Wien filter given by

$$\phi_0^{\mathrm{WF}} = 2.53 \pm 0.02 \text{ mrad},$$

$$\chi_0^{\mathrm{sol}} = -3.39 \pm 0.03 \text{ mrad}.$$

This large tilt of the axis suggests that our result is mainly dominated by systematic effects that arise from magnetic imperfections in the ring. Currently, the work for simulating the realistic

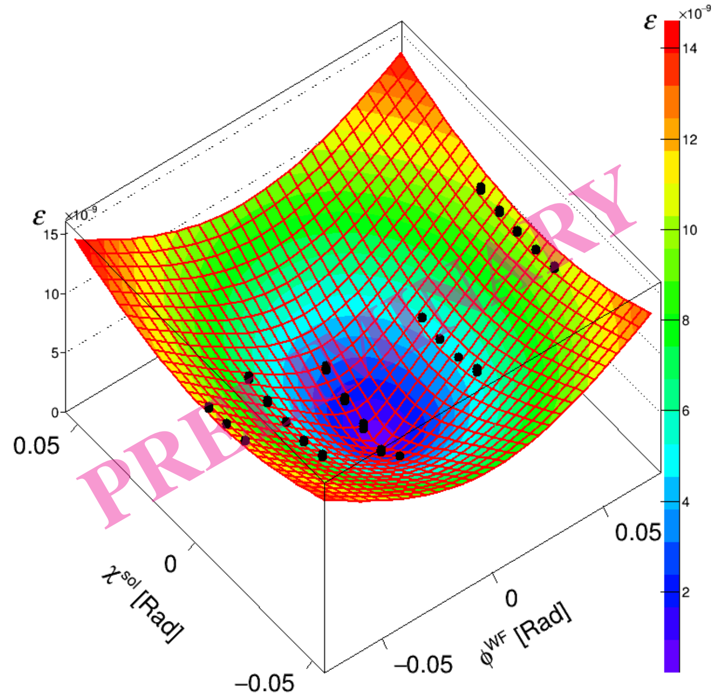

Figure 5: Map of the resonance strength $\varepsilon^{\mathrm{EDM}}$ (see Eq. (3)) for various Wien filter angle ϕ^{WF} and solenoid spin rotation angle χ^{sol}.

COSY ring and further investigations regarding magnetic imperfections leading to systematic effects is ongoing.

3. Conclusion and Outlook

Electric Dipole Moments are a crucial tool for probing possible sources of CP-violation beyond the SM. Storage rings could be used for the search of the EDMs of charged particles. To this end, the first measurements of the deuteron EDM were performed at the Cooler Synchrotron COSY at Forschungszentrum Jülich, Germany. The observed result is predominantly influenced by systematic effects that stem from magnetic imperfections present in the ring. Thus, extensive efforts are underway to further investigate these systematic effects, with the aim of differentiating them from the EDM signal. This would conclude the first stage of the JEDI project. The second stage addresses a prototype ring that will employ deflector elements that will provide purely electric fields or combined electric and magnetic bending. This ring would allow for the operation of clockwise and counter-clockwise circulating beams in what is known as the frozen spin condition. This intermediate stage is necessary in order to address all the challenges concerning all electric ring operation, and the clockwise-counter clockwise beam operation with orbit differences up to few picometers and other aspects. For the second stage, the proposal "PRESTO" has been submitted as a Design Study in the framework of Horizon Europe (see last column of Fig. 1 for the expected level of precision of this stage). Finally, the third stage aims to build a dedicated all electric ring for highest precision measurements of the proton EDM, aiming at a sensitivity of $10^{-29}\mathrm{e}\cdot\mathrm{cm}$ (see last column on Fig. 1).

4. Acknowledgements

This work was supported by the ERC Advanced Grant (srEDM #694340) of the European Union. I am very grateful to Frank Rathmann and Volker Hejny for attentive reading of this document and providing many valuable suggestions.

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