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Search for Electric Dipole Moments and Axions/ALPS with Polarized Beams in Storage Rings

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The research investigates two main questions in particle physics and cosmology: the fate of antimatter after the Big Bang and the nature of Dark Matter (DM). It focuses on studying Electric Dipole Moments (EDMs) in particles like protons and deuterons using polarized particle beams in a storage ring. Research and developments have been till now experimentally pursued at the COoler SYnchrotron (COSY) storage ring at Forschungszentrum-Jülich in Germany which has been shut-down at the end of 2023. The next stage involves designing a Prototype Storage Ring (PSR), both all-electric and hybrid (electric and magnetic), with a beam energy of 30-45 MeV and a circumference of around 100 m. The PSR aims to prepare for a final EDM facility, addressing technical uncertainties for measuring a proton EDM. Following the PSR phase, a precision EDM facility with 233 MeV energy and 500 m circumference will seek to significantly enhance the neutron's static EDM limit, potentially leading to significant discoveries.

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1. Introduction

Subatomic particles with non-zero spin, regardless of whether they are elementary or composite, can only possess a permanent Electric Dipole Moment (EDM) if both time-reversal (T) and parity (P) symmetries are explicitly violated, while maintaining charge-conjugation (C) symmetry. Assuming the conservation of CPT symmetry, the violation of T also implies the violation of CP. Stemming from the Kobayashi-Maskawa mechanism in weak interactions ([1]), CP violation contributes a minute EDM well below current experimental thresholds. Nevertheless, numerous models Beyond the Standard Model (BSM) anticipate EDM values close to existing limits ([2]). Detecting a non-zero EDM in any subatomic particle would signal the presence of new CP violation, possibly triggered by strong CP violation through the q-QCD angle or a distinct BSM phenomenon. The tightest upper limit on q-QCD emerges from the neutron's EDM bound ([3]). BSM CP-violation is pivotal for elucidating the Baryon-Antibaryon Asymmetry (BAU) in our Universe. However, assessing a solitary EDM, such as that of the neutron, will not adequately pinpoint the origins of new CP violation; consequently, simultaneous observations of EDMs across various systems are crucial. Historically, EDM measurements have primarily targeted neutral systems like neutrons, atoms, and molecules. Figure 1 ([4]) shows the summary of EDM upper bounds: notably, the proton's limit is indirectly deduced from a ^{199}Hg measurement, while no limit for the deuteron currently exists. To provide the direct EDM measurement for charged particles, a specialized precision storage ring ([5]) has to be engineered allowing the study of the temporal changes in polarization of the stored polarized beams comprising protons and/or deuterons.

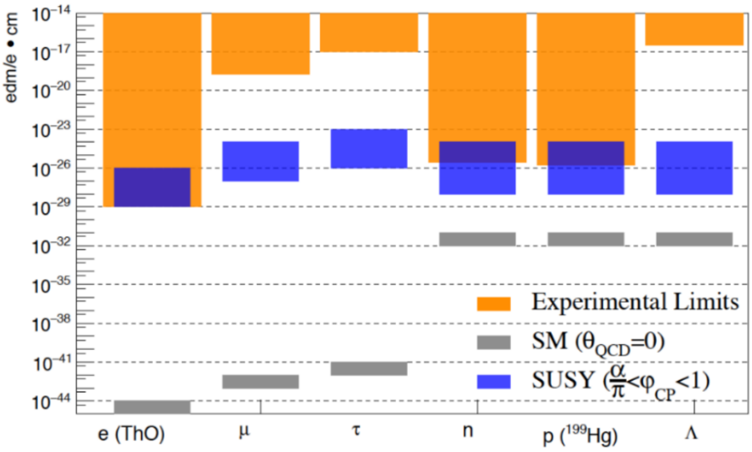


FIGURE 1
Plot of the present experimental limits (orange), the SM predictions (grey) and the SUSY predictions (blue) for the EDM of various particles.

Dark Matter (DM) was postulated to resolve discrepancies in observed mass compared to rotating galaxies necessary for gravitational binding and counteracting centrifugal forces. Additional evidence supporting DM's existence includes gravitational lensing and its role in shaping the Universe's structure. Despite these observations, the true nature of DM remains elusive. Notably, none of the known constituents of the successful SM of particle physics can account for DM. This discrepancy indicates the model's incompleteness emphasizing that the discovery of DM particles would signify physics BSM. Although dedicated experiments continue to search for DM, no conclusive observations have been made to date, despite some claims. The vast range of permissible DM parameters, such as mass and interactions with standard model particles, necessitates diverse discovery techniques. Current strategies for DM detection include:

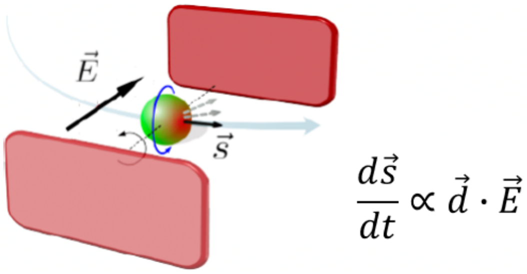
- direct production: generating DM particles at accelerators;
- galactic interactions: detecting galactic DM particles via interactions with SM matter;
- oscillating waves detection: identifying DM through coherent oscillations.

The search for DM with respect to EDM will leverage the third option, focusing on observing DM particles through their manifestation as oscillating EDMs in nucleons and nuclei. This approach aims to detect the effects on spin motion in a particle ensemble within a storage ring. By conducting an oscillation-frequency resonance scan, researchers can explore a broad spectrum of axion masses, covering multiple orders of magnitude.

2. Principle of EDM measurement in a storage ring

When a particle interacts with an electric field (**E**) through its EDM (**d**), its spin undergoes a torque (∝**d**×**E**) and starts to precess. This precession is akin to the behaviour of a classical gyroscope responding to the gravitational force of the Earth. As depicted in Figure 2, a particle is maintained on its orbit by the transverse electric field produced by the red electrostatic deflector plates: initially the spin (**s**) is aligned with the direction of motion, but then the EDM alters the orientation of the spin moving it out of the ring plane through a torque due to the interaction with the electric field. Detecting this spin precession is crucial for identifying and quantifying the EDM of the particle. This effect can be observed experimentally by using a polarimeter, which reveals itself as a left-right asymmetry. However, this kind of detection poses significant challenges due to its anticipated minuteness:

- detecting the subtle changes in the spin direction of a single particle in an electric field is impractical; instead, an ensemble of particles must be examined and the polarization, i.e. the average spin direction, of the particle cluster becomes the observable of interest;
- when charged particles are subjected to electric fields, they get deflected; therefore, a containment mechanism, such as a storage ring, is necessary to confine the particles during the measurement process;
- apart from the EDM, particles with spin also possess a much stronger Magnetic Dipole Moment (MDM); unwanted interactions of the MDM with magnetic fields need to be minimized or eliminated to ensure accurate EDM measurements.



$$\frac{d\vec{s}}{dt} \propto \vec{d} \cdot \vec{E}$$

FIGURE 2

Illustration of the fundamental concept for the EDM measurement. For clarity, only one particle is depicted and the precession of the MDM is disregarded. The electric field E is applied in the center of mass system of the particle.

A full account of the time development of a particle spin in electro-magnetic fields is given by the Thomas-BMT equation ([6]). It is of utmost importance to minimize or better to get rid of the

MDM effects; otherwise, there is no chance whatsoever to reach a competitive sensitivity for the EDM. One principal possibility to achieve this for protons is to build an all-electric ring and to operate it at the so-called "magic momentum" of 700.7 MeV/c (energy of 232.8 MeV).

3. Measurements at the COSY storage ring

3.1 Measurement of the static EDM of the deuteron

Two runs of the deuteron EDM measurement have been performed at the COoler SYnchrotron (COSY) in December 2018 and March 2021 aimed at determining the invariant spin axis (**n**), a vital parameter directly linked to the EDM defined as the axis around which the spins precess. In an ideal scenario, the particle possesses only a MDM and the invariant spin axis aligns vertically along the magnetic guiding field (**M**). When an EDM is introduced, the invariant spin axis deviates towards the radial direction by an angle proportional to the sum of the MDM and EDM contributions. The experiment used a radio frequency Wien filter ([7]) to induce a vertical polarization component build-up by creating a tilt in the invariant spin axis concerning the Wien filter's magnetic field axis. By rotating the Wien filter around the beam axis and introducing a solenoidal field, it is possible to intentionally adjust the invariant spin axis in radial and longitudinal directions. The process involves assessing the polarization build-up through measuring a resonance strength (referred to as "ε" in accelerator terminology) relative to these rotations. This approach enables the generation of a two-dimensional map, with the minimum value pinpointing the location of the invariant spin axis under the standard conditions of the Wien filter in its original position and no solenoidal field applied. Figure 3 depicts the evolution of the ratio $\alpha = \text{atan}(P_v/P_h)$, where P_v and P_h are the vertical and horizontal polarization components respectively, over time for a fixed configuration of the Wien filter and the solenoid. When the Wien filter is activated, the vertical component starts increasing, indicating a rise in vertical polarization. The slope is directly tied to the resonance strength.

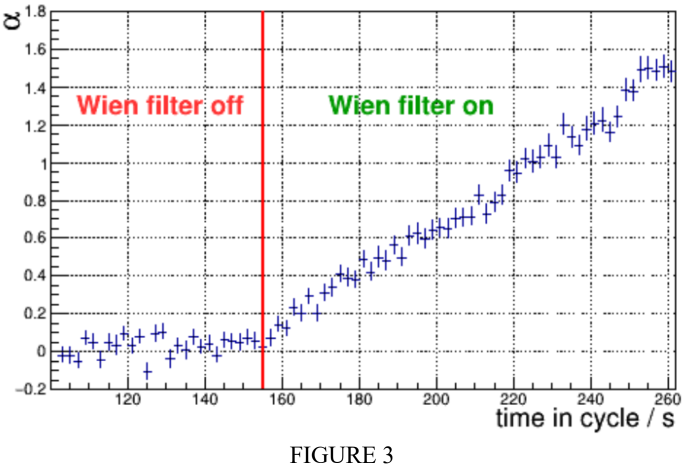


FIGURE 3
Plot of the ratio $\alpha = \text{atan}(P_v/P_h)$ as a function of time.

In Figure 4 the relationship between the resonance strength and the rotation angles induced by the Wien filter and the solenoidal field is illustrated. The map's minimum signifies the position of the invariant spin axis with the Wien filter in its default position and no solenoidal field applied. While an ideal case would anticipate a radial tilt of the invariant spin axis due to an EDM in a ring, observations reveal both longitudinal and radial tilts at a few mrad which can be attributed to systematic influences like element misalignments being investigated using beam and spin tracking simulations. A 1 mrad radial tilt corresponds to an EDM of 10^{-17} e·cm.

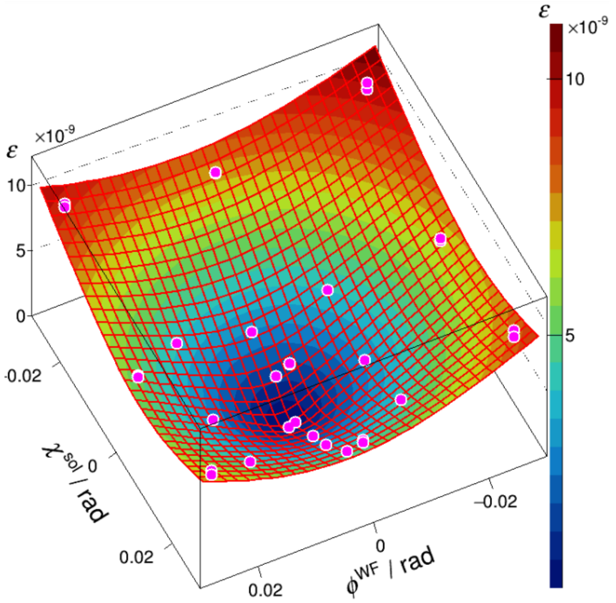


FIGURE 4

Plot of the measured resonance strength ε as a function of the RF-Wien filter rotation angle ϕ^{WF} and the solenoidal field rotation angle χ^{sol} (spin kick). The coloured area shows a fit with a two dimensional paraboloid to the data and the minimum of the map indicates the position of the invariant spin axis.

3.2 Measurement of the oscillating EDM of the deuteron

An Axion-Like Particle (ALP) or simply axion can generate an oscillating EDM with the oscillation frequency linearly linked to the particle's mass. When the resonance condition is met leading to vertical polarization accumulation, the resonant frequency coincides with the MDM. The MDM is specifically determined in a purely magnetic ring environment; consequently, by scanning through different frequencies, various axion masses can be explored in axion searches. The JEDI (Jülich Electric Dipole moment Investigations) collaboration undertook scans within a defined range corresponding to masses between 4.95×10^{-9} V to 5.02×10^{-9} V. Further details on the analysis can be found in reference ([8]). Despite observations revealing no signal, preliminary results indicate 90% confidence limits determined from statistical sensitivity. The detectability is characterized by an oscillating EDM comparable to a precision of about 10^{-22} e·cm and proves less susceptible to systematic effects compared to the pursuit of a permanent EDM. The measurement can be translated to an axion-EDM coupling constant, as shown in Figure 5.

4. Design of a new storage ring

Having resolved key R&D challenges and finalized proof-of-principle experiments for both static and oscillating EDM investigations at the COSY magnetic storage ring, the logical progression, as per research by JEDI and CPEDM collaborations, is the development of a Prototype Storage Ring (PSR) ([9]).

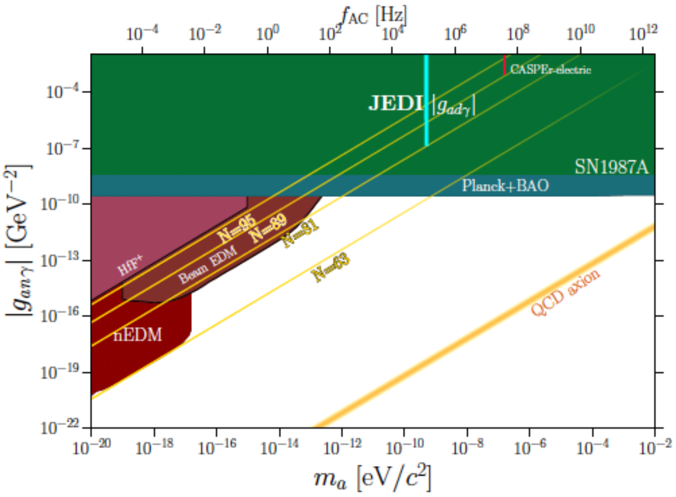


Figure 5

Plot of the axion-EDM coupling as a function of the axion mass m_a from various experiments.

This initiative encompasses the following objectives:

- formulating the PSR lattice design for an all-electric and a combined electric-magnetic ring, along with cost estimations for various scenarios involving host labs and different phases;
- conducting simulations to ascertain the EDM and axion search sensitivities achievable with the PSR setup;
- exploring the potential of a combined electric-magnetic deflector element.
- creating and validating an advanced polarimeter design surpassing current capabilities.

The PSR will pave the way to a final full electrostatic storage ring (see Figure 6).

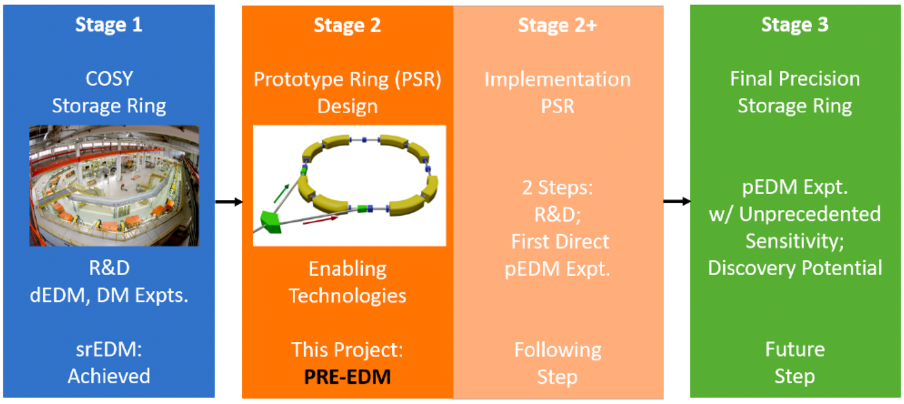


FIGURE 6

Figure illustrating the progression towards establishing a high-precision storage ring facility for charged particle EDM investigations involves several stages.

4.1 Spin-coherence time optimization

The spin tune and the SCT are two fundamental and strictly connected quantities to consider when performing an EDM experiment in a storage ring.

The spin tune of a single particle is the number of spin precessions around the vertical axis per turn of the particle around the ring and is defined as ([10]):

$$\nu_s = G\gamma,$$

where G is the gyro-magnetic anomaly and γ is the relativistic factor.

The SCT represents the time interval during which the spins of all the particles of the stored beam precess coherently, maintaining a net polarization greater than 1/e. Since this condition is necessary for the EDM measurement, it also represents the time available for the experiment, which must be as long as possible. However, since the spin tune depends on particle velocity through the relativistic factor, any mechanism which manifests as the change in particle velocity directly affects the spin tune and as a result each particle is characterized by its own change in the spin tune, the spins spread out and the polarization is lost. To obtain a long spin coherence time, it is necessary to minimize the spin tune.

In this regard, a model that accurately tracks the spin tune has been developed. The starting point was the formula describing the dependence of the path length in a storage ring. [11]. The single particle spin tune formula is expressed by a sum of contributions taking into account the dependences of the spin tune on the synchrotron and betatron motions together with chromaticity in both the horizontal and vertical directions:

$$\langle \nu_s \rangle = \langle \vec{\epsilon} \rangle \cdot \vec{m} + \langle \vec{\epsilon} \rangle \cdot \left(N \vec{\xi} \right),$$

where $\langle \vec{\epsilon} \rangle$ is the time-averaged beam properties vector, $\vec{m}$ and N are respectively the vector and the matrix of the "lattice coefficients" which are determined by the positions and configurations of the components of the lattice, and $\vec{\xi}$ is the second-order optical properties vector. Setting the left-hand side to zero gives us a condition on the second-order optical properties which minimizes the spin tune of a particle in a way that is independent of the beam properties. This would mean that at this setting, the beam is highly likely to behave coherently.

The spin tune model has been tested in a variety of lattices representing existing storage rings as well as a future class of dedicated storage rings. These lattices differ in the combination of electric and magnetic fields used for particle confinement and the number of sextupole families. One of these is the PSR described in the previous section and the preliminary results have been already published ([12]); another one is the hybrid ([13]) and the results will be published soon in *Nuovo Cimento*. The study has explored the implications of the spin tune model on the SCT optimization. The spin tune model outcomes have been verified by comparison to those of the brute force searches of configurations with SCTs of more than 1000 seconds. The result was a deeper mathematical understanding of the spin tune phenomenon as well as a method to find the setting which optimizes the SCT much more quickly.

The entire work will be published soon.

5. Conclusions

Electric Dipole Moments (EDMs) are very sensitive probes of CP violation that can be used to explore the physics beyond the Standard Model (SM) and solve some open questions the SM cannot answer. To directly measure the EDMs of charged particles, a new technique which involves the use of the storage rings has been developed. First measurements of the deuteron EDM have been performed at the COoler SYnchrotron (COSY) at Forschungszentrum-Jülich in Germany. To reduce systematic uncertainties, a new type of storage ring has to be constructed: the Prototype Storage Ring (PST).

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