Search for electric dipole moments in storage rings: progress and perspectives

Lenisa Paolo[1]

[1]*University of Ferrara and INFN, Ferrara, Italy*

E-mail: lenisa@fe.infn.it

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The observation of a non zero electric dipole moment of a fundamental particle would represent a clear sign of New Physics beyond the Standard Model. An experimental program is presently pursued by the JEDI Collaboration at the COSY storage ring of the Forschungszentrum Jülich (Germany) to provide the first ever measurement of the electric dipole moment of the deuteron. The gained experienced and developed technologies result important in perspective of the design and realization of a future dedicated storage ring.

KEYWORDS: Storage rings, Polarized beams, Electric and magnetic moments, Discrete symmetries

1. Introduction

One of the most intriguing questions in cosmology and perhaps in all of physics is: Why is there so much matter in the Universe and so little antimatter?. Until today, there is no evidence for any primordial antimatter within our galaxy or even beyond. There is no indication for any form of co-existence of matter and antimatter in clusters or galaxies within our Universe. Hence, it is usually concluded that our visible Universe is made entirely of matter and is intrinsically matter non-symmetric. According to the combined Standard Models of cosmology and particle physics it is expected that at the end of the inflationary epoch - following the Big Bang - the number of particles and antiparticles were in extreme balance, yet somehow the laws of physics contrived to act differently on matter and antimatter in order to generate the current imbalance. Interestingly, one of the necessary physics mechanisms required for such effects namely CP-violation is very small in the Standard Model (SM) of particle physics and thus is only able to account for a tiny fraction of the actual asymmetry.

While particle physics at accelerators celebrated its latest success with the discovery of the Higgs boson, culminating in a series of discoveries all consistent with the SM, the chances have grown up in recent years that new physics could be at mass scales beyond the reach of current or future collider experiments. This prospect, in combination with astrophysical observations (e.g. dark matter, neutrino oscillations), not explained by the SM has stimulated interest in high-precision physics. One such search for new physics is the quest for electric dipole moments (EDMs) in fundamental particles.

An EDM originates from a permanent electric charge separation inside the particle. In its centre-of-mass frame, the ground state of a subatomic particle has no direction at its disposal except its spin, which is an axial vector, while the charge separation (EDM) corresponds to a polar vector. If such a particle possesses an EDM, it must violate both parity (P) and time-reversal (T) invariance (Fig. 1).

If the combined CPT symmetry is to be valid, T violation also implies breaking of the combined CP symmetry. The Standard Model predicts the existence of EDMs, but their sizes fall many orders of magnitude below the sensitivity of current measurements and still far below the expected levels of

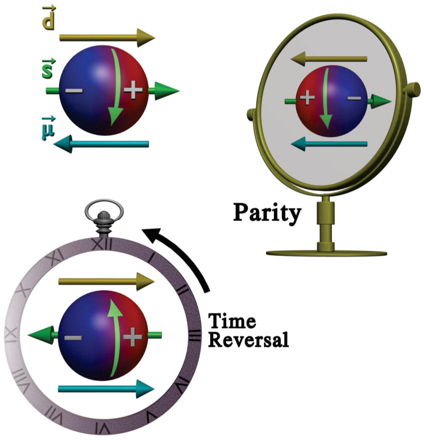

Fig. 1. Naïve representation of a fundamental particle as a spherical object with an asymmetric charge density (upper left). The particle mirror image is represented on the right, and its time-reversal at the bottom. The particle spin defines (**s**) a direction in space. Both P and T transformations leave the magnetic dipole moment (μ) antiparallel to the spin while change the relative orientation of the electric dipole moment (**d**). Therefore, the original particle can be distinguished from its mirror or time reversal image.

projected experiments. An EDM observation at a much higher value might be interpreted as a sign of new physics beyond the current Standard Model (BSM).

Researchers have been searching for EDMs of neutral particles, especially neutrons, for more than 60 years, but, despite a constant increase in sensitivity, the experiments have come up only with upper bounds, nevertheless providing useful constraints on BSM theories (Fig. 2).

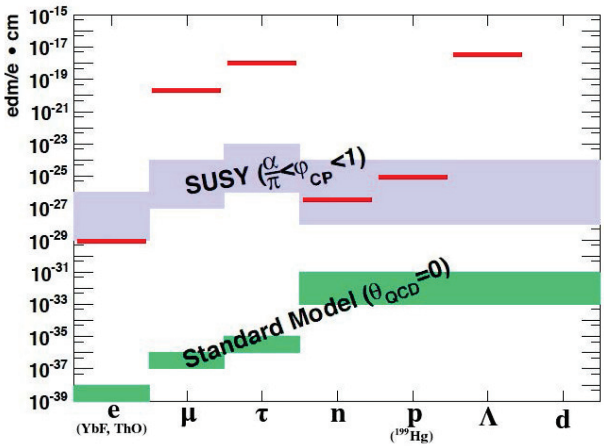

Fig. 2. Experimental upper limits for the EDMs of different particles (red bars) plotted together with the prediction from SUSY (blue bands) and the Standard Model (green bands). No experimental limit for the deuteron exists yet.

2. EDM search in storage rings

More recently, a new class of experiments based on storage rings has been proposed to improve the sensitivity of the measurements and eventually be able to measure the EDM of charged particles (such as the proton, deuteron or helion). The measuring principle is straightforward: a radial electric field is applied to an ensemble of particles circulating in a storage ring with their polarization vector (or spin) initially aligned with their momentum direction. The existence of an EDM would generate a torque that slowly rotates the spin out of the plane of the storage ring and into the vertical plane (Fig. 3).

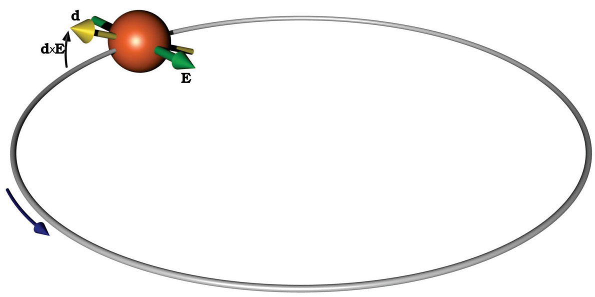

Fig. 3. Measuring principle of a charged particle EDM in a storage ring. A radial electric field is applied to an ensemble of particles circulating in a storage ring with polarization vector aligned to their momentum: the existence of an EDM, would generate a torque that slowly rotates the spin out of the ring plane into the vertical direction.

This slow change in the vertical polarization is measured by sampling the beam with elastic scattering off a carbon target and looking for a slowly increasing left-right asymmetry in the scattered particle flux. For an EDM of 10^{-29} ecm and an electric field of 10 MV/m, this would happen at an angular velocity of 3×10^{-9} rad/s (about 1/100 of degree per day!). This requires the measurement to be sensitive at a level never reached before in a storage ring. These requirements imply that for a statistically significant result, the polarization in the ring plane must be kept for times on the order of a thousand seconds during a single fill of the ring and the scattering asymmetry from carbon must reach levels above 10^6 in order to be measurable within a year of running.

3. Achievements at the COSY storage ring

At the Cooler Synchrotron COSY located at the Forschungszentrum-Jülich (FZJ) (Fig. 4), the JEDI Collaboration [1] is working on a series of feasibility studies for the EDM experiment in a to-be-built dedicated storage ring. The COSY ring, able to store both polarized proton and deuteron beams, is an ideal machine for the development and commissioning of the necessary technology.

3.1 Measurement of the spin-tune

Following the commissioning of a measurement system that stores the clock time of each recorded event in the beam polarimeter, some major achievements have been already realized. The polarized beam is injected into COSY with the polarization vertical. Operating a radio-frequency solenoid for a brief period turns the polarization into the ring plane and subsequently the measurements are started. Above all, it was possible to unfold for the first time the rapid rotation of the polarization in the ring plane ($\approx$ 120 kHz) arising from the gyromagnetic anomaly. The spin tune (i.e. the number of spin precessions per turn) has been measured with a precision better than 10^{-10} in a cycle of 10 seconds

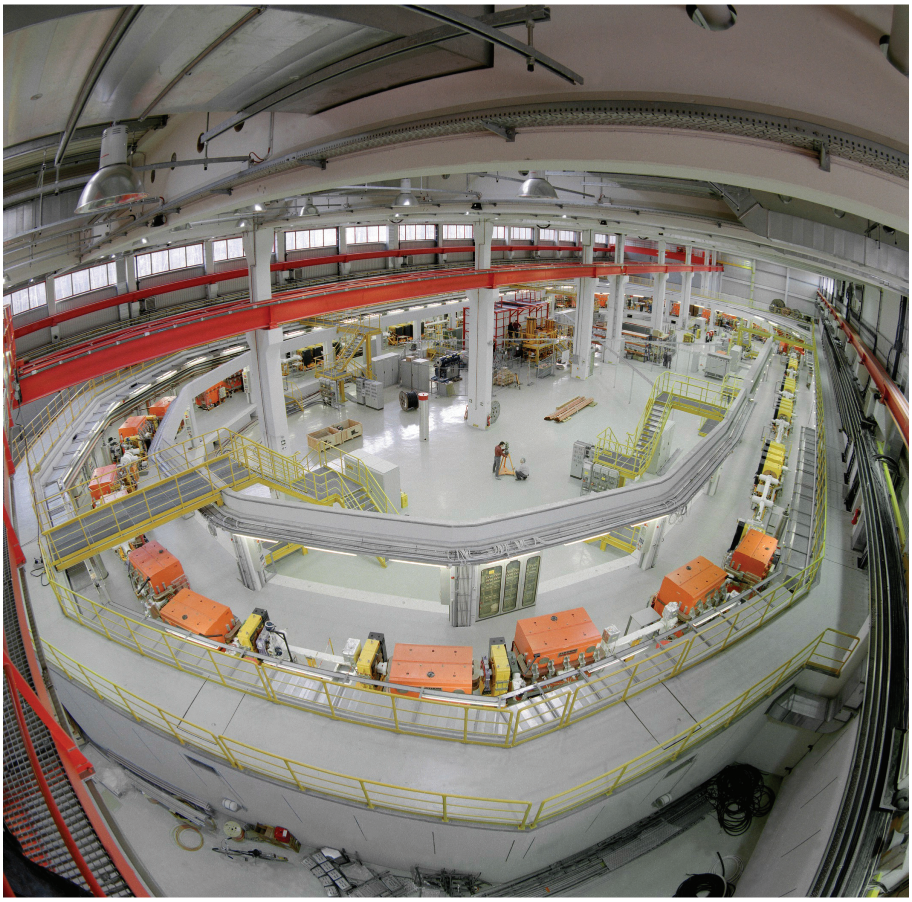

Fig. 4. The COSY storage ring at the Forschungszentrum Jülich.

that possibly represents the most precise measurement ever performed in a storage ring (Fig. 5) [2].

3.2 Spin-feedback system

It was also demonstrated that, by determining the errors in the polarization direction and feeding this back to make small changes in the ring radio-frequency, the direction of the polarization may be maintained at the level of 0.1 radian for any chosen time period. This is another requirement needed for managing the polarization in the ring for the EDM experiment (Fig. 6) [5].

3.3 Spin-coherence time

Another milestone was the achievement of polarization lifetimes in the ring plane longer than 1000 s (Fig. 7) [3].

Maintaining the polarization in the ring plane requires the cancellation of effects that may cause the particles in the beam to differ from one another. Bunching and electron cooling the beam serves to remove much of this spurious motion. However particle path lengths around the ring may differ if particles in the beam have transverse oscillations with different amplitudes. The effect of these differences on polarization decoherence may be removed by applying correcting sextupole fields to the ring. As a result, the polarization lifetimes now reach the required duration for the EDM experiment.

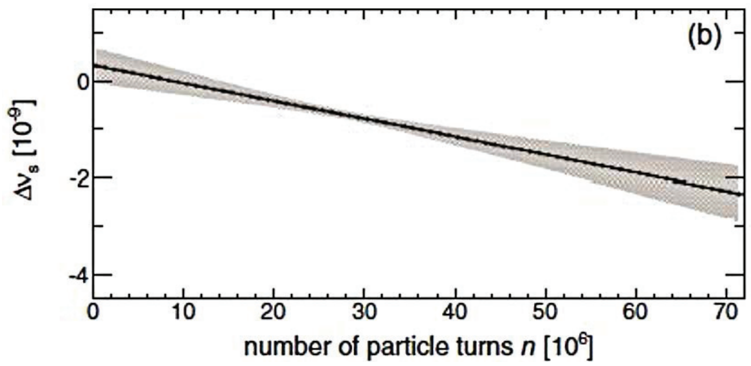

Fig. 5. Deviation of the spin tune s, which is defined as the number of spin precessions per turn, as a function of the number of turns in the ring. At t = 38 s (about 28 $\times 10^6$ turns), the interpolated spin tune amounts to 16097540628.3 ± 9.7 10^{11}, which represents the most precise measurement of this quantity ever performed.

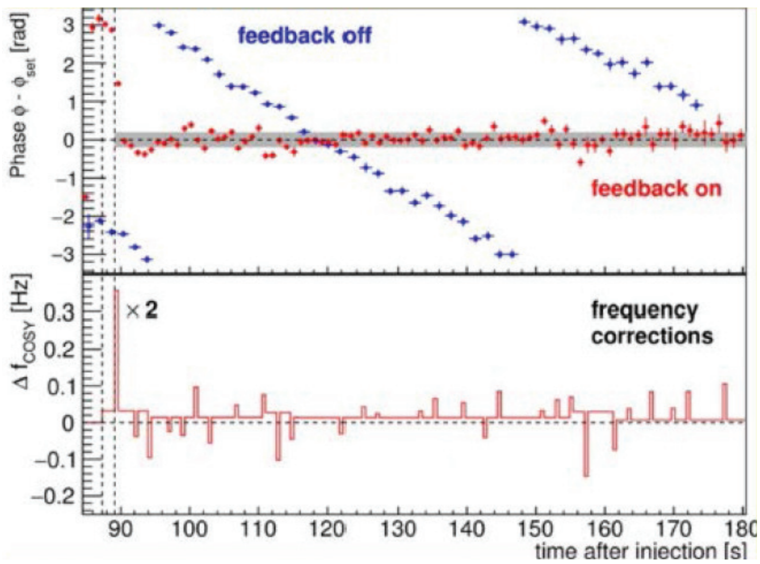

Fig. 6. Operation of the active spin-feedback system. Spin-phase of the beam relatively to en external reference without and with use of the feedback system (upper picture) together with correction signals (lower picture).

4. Towards the first measurement of the deuteron EDM

In 2016 the European Research Council awarded an Advanced Research Grant to the Juelich group, supporting further R-D efforts [6]. The goal of the project is to conduct the first ever measurement of the deuteron EDM. Since at COSY the polarization cannot be maintained parallel to its velocity, a novel device called a radiofrequency Wien filter [4] has been installed in the ring to slowly accumulate the EDM signal: the filter influences the spin motion without acting on the particles orbit. The idea is to exploit the electric fields created in the particle rest system by the magnetic fields of the storage-ring dipoles (Fig. 8).

As the particles spin precesses with a different frequency with respect to the velocity, the net contribution to the polarization buildup coming from the motional E-fields per turn would average to zero. The radiofrequency-Wien filter, synchronized with the spin precession frequency, would re-

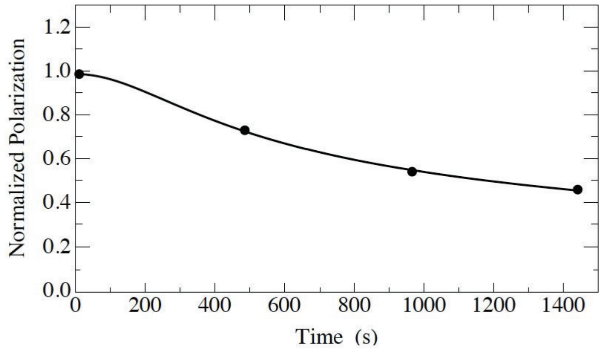

Fig. 7. One of the longest polarization lifetimes recorded for the COSY ring. Measurements made at four separate times (to conserve beam) are matched to a depolarization curve that assumes a Gaussian distribution of transverse oscillation amplitudes. The half-life of the polarization is 1173 ± 172 s, which is three orders of magnitude longer than previous results using electron beams.

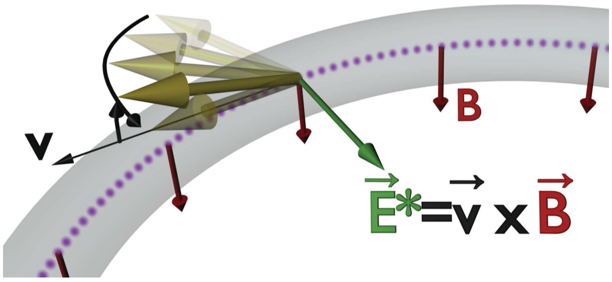

Fig. 8. First measurement of the deuteron EDM as planned at COSY. The spin precesses in the vertical magnetic fi eld of the dipoles and feels a torque caused by the interaction of the EDM with the electric motional field. To allow for polarization buildup to occur, an RF-Wien filter will be used to control the relative phase between spin and momentum

store the parallelism between spin and momentum and allow the polarization build-up to take place. A prototype of the radiofrequency-Wien filter with separate components has been successfully commissioned and tested at COSY in 2014. A new device with a stronger magnetic field (0.05 Tmm) based on waveguide concept [4], was subsequently developed and constructed together with the Institut für Hochfrequenztechnik (IHF) at RWTH Aachen University and ZEA-1 in Jülich. This new radiofrequency Wien-filter was installed in COSY in May 2017. A first commissioning run was successfully conducted in June 2017.

In the test, the B field was oriented in the radial direction, and its force on the stored deuterons was perfectly cancelled by the vertical electric one: the device could be used to continuously flip the vertical polarization of a 970 MeV/c deuteron beam without exciting any coherent beam oscillations. In the EDM experiment, the radiofrequency-Wien filter will be rotated by 90 degrees around the beam axis, so that the B field will point in the vertical direction and consequently act on the spins of the particles precessing in the horizontal plane. To accomplish to the task, the frequency of the Wien filter will be locked to the spin motion of the particles by a novel developed spin-feedback system [5]. The most significant challenges will come from the management of systematic errors. Small imperfections in the placement and orientation of ring elements may cause stray field components that generate the accumulation of an EDM-like signal. The experiment is most sensitive to radial magnetic fields and vertical electric fields. Similar effects may arise through the non-commutativity of spurious rotations within the ring system. Efforts are underway to model these effects through spin tracking supported with beam testing. Eventually, many such effects may be reduced or eliminated by comparing the signal accumulation rates seen with beams traveling in opposite directions in the storage ring.

5. Future perspectives

The commissioning of the radiofrequency-Wien Filter and the demonstration of its control over the particles spin will represent a fundamental milestone towards the design and realization of the final high-precision ring with a EDM sensitivity goal of 10^{-29} e.cm or even better. This will necessarily require the use of clockwise (CW) and counter-clockwise (CCW) beams to remedy systematic errors like: radial magnetic fields, non-radial electric fields, vertical quadrupole misalignments, rf-cavity misalignments and unwanted field components. As the matter of fact, the main systematic error coming from an unwanted spin precession due to the MDM in radial magnetic fields (which is indistinguishable from the EDM signal) can be controlled to a very high accuracy in the CW-CCW scheme, as the very same radial magnetic field causes forces in different directions for two opposite beams (Fig. 8).

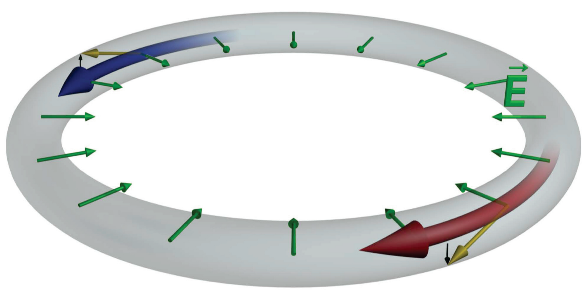

Fig. 9. Concept of a dedicated ring for the measurement of an electrical dipole moment (proton case). The control of systematic effects suggests the use of two particle beams circulating in opposite directions in a *pure electrostatic* ring. Keeping the polarization vector aligned with momentum (*frozen-spin* condition), the interaction of en exisiting EDM with the electric field, would generate a torque slowly rotating the spin out of the plane of the storage ring into the vertical direction. Note that ehe EDM induced rotation will have different directions in the two beams. For the case of the proton, the frozen-spin condition is realized with a beam impulse of p = 700.7 MeV/c (*magic momentum*). In this situation there is no spin precession in the accelerator plane due to the magnetic moment.

Also in view of the possible construction of a dedicated EDM ring, COSY constitutes an important test facility of many EDM related key technologies. Besides polarimetry, beam position monitoring and active control systems, also the design of electrostatic and electromagnetic deflectors benefits by direct test in a storage rings. In addition, checks for systematic errors can be undertaken for further developments and applications.

Recently also CERN demonstrated interest in the perspectives offered by storage-ring EDM searches. A working group has been being established in Collaboration with the Jülich team to provide a feasiblity study of a proton EDM storage ring.

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