Search for Electric Dipole Moments and Axions/ALPs in storage rings

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ESPP

European Strategy for Particle Physics

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Motivation and Methodology

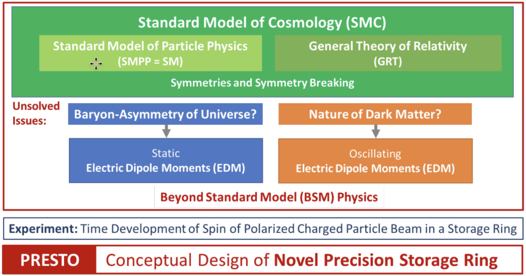
Physics case

Addressed issues

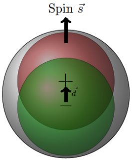
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

Experimental approach

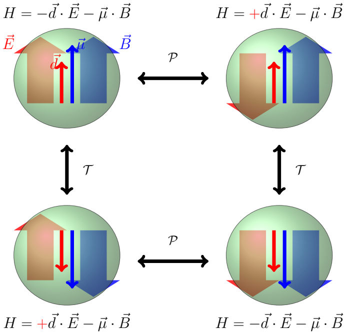
- Measurements of static Electric Dipole Moments (EDM) of fundamental particles.
- Searches for axion-like particles as DM candidates through oscillating EDM



Electric Dipole Moment (EDM)



- Permanent separation of + and - charge
- Fund. property of particles (like mag. moment, mass, charge)
- Possible via violation of time-reversal (T) and parity (P)



$$H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} - d\frac{\vec{s}}{s}\cdot\vec{E}$$

- T: $H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} + d\frac{\vec{s}}{s}\cdot\vec{E}$
- P: $H = -\mu\frac{\vec{s}}{s}\cdot\vec{B} + d\frac{\vec{s}}{s}\cdot\vec{E}$

EDM meas. test violation of P and T symmetries ($\stackrel{CPT}{=}$CP)

CP-violation & Matter-Antimatter Asymmetry

Matter dominance:

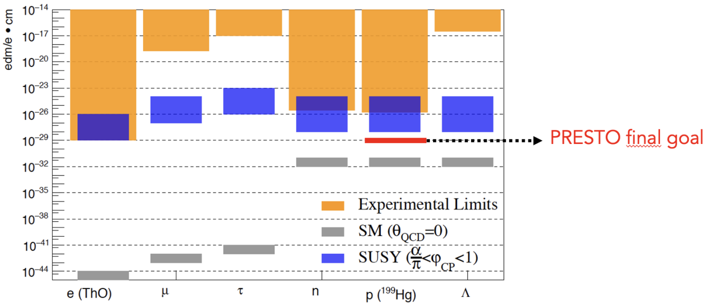
- Excess of Matter in the Universe:

$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$	observed	SM prediction
	6×10^{-10}	10^{-18}

- Sacharov (1967): CP-violation needed for baryogenesis

- $\Rightarrow$ New CP-V sources beyond SM needed
- Could show up in EDMs of elementary particles

Static EDM upper limits



Direct EDM measurements missing

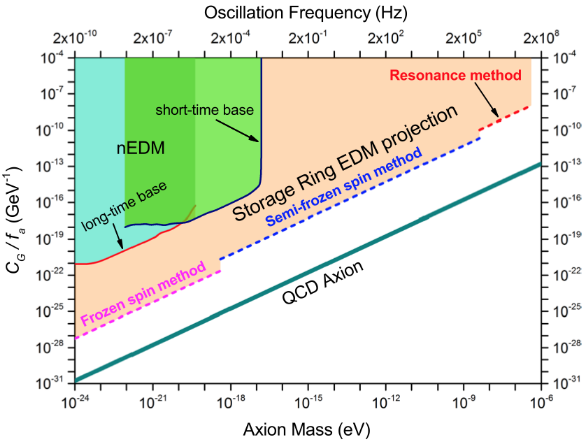
- No direct measurements of electron: limit obtained from (ThO molecule).
- No direct measurements of proton: limit obtained from $^{199}_{80}Hg$.
- No measurement yet of deuteron EDM.

Theory:

- EDM of single particle not suffcient to identify CP violating source

J.M. Pendlebury: "EDM has killed more theories than any other single experiment"

Axion Dark Matter search with Storage Ring EDM method

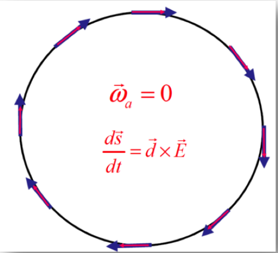


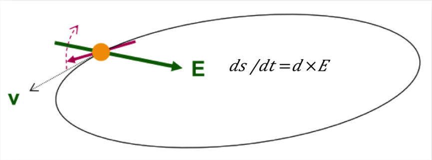
- Experimental limits for axion-gluon coupled oscillating EDM measurements

Search for static EDM in storage rings

Storage ring method to measure EDM of charged particle

1. Inject beam of polarized particles in storage ring
2. Align spin along momentum ($\rightarrow$ freeze horiz. spin-precession)
3. Search for time development of vertical polarization





Achievements at the COSY Storage Ring

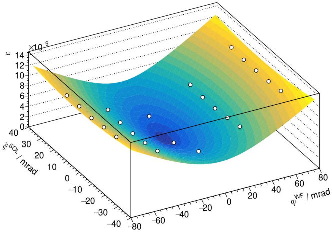
Results from dEDM precursor experiment

EDM resonance strength map for ϵ^{EDM}

- Includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.

Preliminary result on static EDM

- Determination of minimum via fit with theoretical surface function yields:
  - ϕ_0^{WF} (mrad) = - 2.05 $\pm$0.02
  - ψ_0^{sol} (mrad) = + 4.32 $\pm$0.06



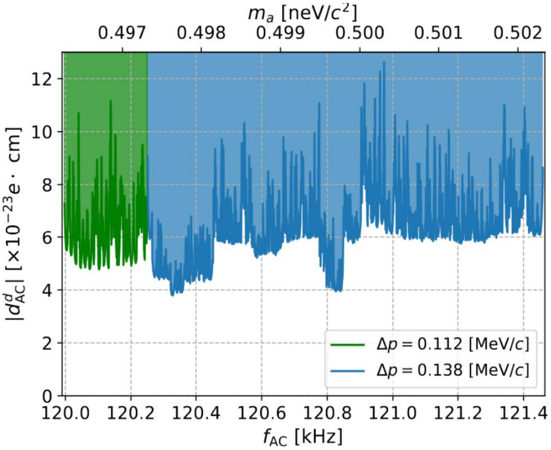
Extraction of EDM

1. Minimum determines spin rotation axis (3-vector) at RF WF, including EDM
2. Spin tracking in COSY lattice $\rightarrow$ orientation of stable spin axis w/o EDM
3. EDM is obtained from the difference of 1. and 2.

EDM analysis presently focused on systematics

- Data analysis close to final & EDM results in preparation.
- Goal: Describe observed tilts of stable spin axis by spin tracking

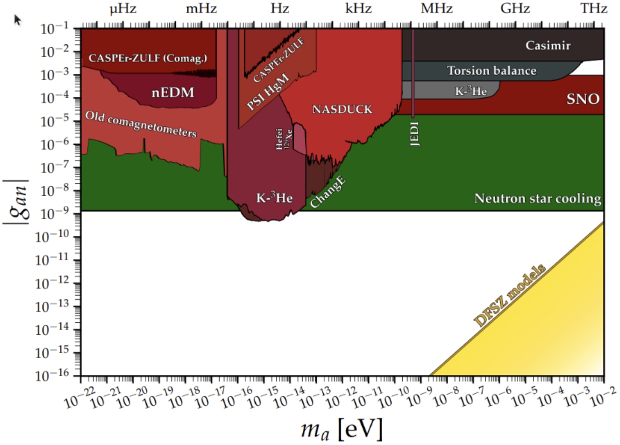
Bound on oscillating EDM of deuteron



Observed oscillation amplitudes from 4 bunches

- 90 % CL upper limit on the ALPs induced oscillating EDM
- Average of individual measured points $d_{AC} < 6.4 \times 10^{-23}$ e cm

Bound on axion-nucleon coupling



Limits on axion/ALP neutron coupling from the Particle Data Group

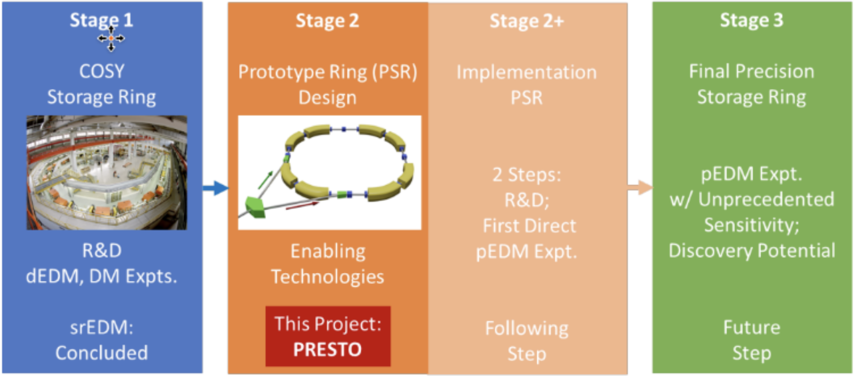
- It includes the result from the JEDI collaboration
  - S. Karanth et al., Phys. Rev. X 13 (2023) 031004

Next steps

Objective: construction of a dedicated SR for EDM studies

Possible approaches

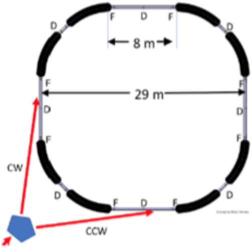
- Staged approach
- One step approach



Stage 2: prototype EDM storage ring

100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- Frozen spin including additional vertical magnetic fields



Challenges

- All electric & E-B combined deflection
- Storage time
- CW-CCW operation → next slide
  - Orbit control
  - Control of orbit difference
- Polarimetry
- Spin-coherence time
- Magnetic moment effects
- Stochastic cooling

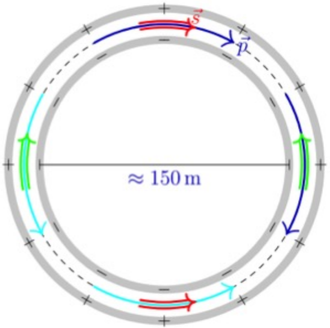
Objectives of PTR

- Study open issues.
- First direct proton EDM measurement.

Stage 3: precision EDM ring

500 m circumference (with E = 8 MV/m)

- All-electric deflection
- Magic momentum for protons (p = 707 MeV/c)



Challenges

- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($>$ 1000 s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual B_r fields

"Holy Grail" storage ring (largest electrostatic ever conceived)

Conclusions

EDM searches in Storage Rings

- Outstanding scientific case with high discovery potential
- Key developments in accelerator technology

Fundamental achievements at COSY

- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

Next steps

- Feasibility study of a *pure electrostatic* EDM proton ring
- Possible approches
  - Staged approach
  - Direct approach

Excellent opportunity

- Interdisciplinary impact
  - Fundamental and particle physics
  - Astroparticle and hadron physics
  - Accelerator and data science

Implementation in the ESPP document

- *Charged particle Electric Dipole Moment (cpEDM) measurements (C. Carli, P. Lenisa)*
  Proposals to build a synchrotron to measure a possible EDM of charged particles are motivated by the physics case described in section 5.7. Whereas the Electric Dipole Moment (EDM) of electrically neutral particles as neutrons can be measured with particles at rest, cpEDM measurements require to confine the particles in a precision storage ring. Most proposals to measure static EDMs are based on circulating polarized bunches satisfying the "frozen spin" condition as sketched in Fig. 3. In a perfect machine and particles without EDM and the well known Magnetic Dipole Moment of the particles, an initial longitudinal polarization is maintained by appropriate choice of the magnetic and electric field bending the beam. This means that the angular frequencies ω_M describing the rotation of the spin and ω_p describing the rotation of the particle momentum or direction are identical. A finite EDM generates a rotation of the polarization out of the horizontal plane into the vertical direction. A common proposal [112] by an international community for proton EDM measurements is a ring with only electrostatic bendings operated at the "magic energy" ($\approx$232.8 MeV), where the magnetic fields to satisfy the frozen spin condition vanish. Focusing can be done with electric or magnetic quadrupolar components and a typical circumference is 500 m to keep the electric fields at reasonable values.

  The main challenge of cpEDM measurement proposals is to show that the achievable sensitivity, i.e. the smallest detectable EDM, is superior to current limits, e.g. for the neutron [113]. This requires that a sufficient spin coherence time can be reached and that systematic effects, i.e., spin rotations caused by machine imperfections for particles with an MDM only, can be understood and sufficiently suppressed. The former requires that the beam is bunched and sextupole families are used to suppress contributions to spin decoherence related to betatron and synchrotron oscillations. Some systematic effects are mitigated for "magic energy" rings by circulating counter-rotating beams, state-of-the-art magnetic shielding (in particular for fully electrostatic rings), magnetic focusing and high symmetry lattices (in particular for the "hybrid" ring with magnetic focusing). However, many possible systematic effects remain and require thorough studies thoroughly and careful evaluations.

  A proposal to design and construct a smaller $\approx$ 100 m circumference prototype EDM ring [112] is motivated by the observation that archiving the required cpEDM measurement sensitivity is very challenging without thorough in-depth investigations. Such a prototype ring would be am intermediate step to gain expertise in operating a large scale electro-static facility, to develop key technologies required as very sensitive beam position pick-ups and high electric field equipment, and to study in-depth systematic effects and mitigation measures.