Small Polarized Electron Storage Ring for Fundamental Physics Experiments

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Outline

- Spin transparency and figure-8 storage rings
- Measurement of Electric Dipole Moment of free electron
- Search for axions
- Summary

Riad Suleiman, Vasiliy S. Morozov and Yaroslav S. Derbenev, "High precision fundamental physics experiments using compact spin-transparent storage rings of low energy polarized electron beams", Physics Letters B, Volume 843, 2023, 138058, ISSN 0370-2693, https://doi.org/10.1016/j.physletb.2023.138058

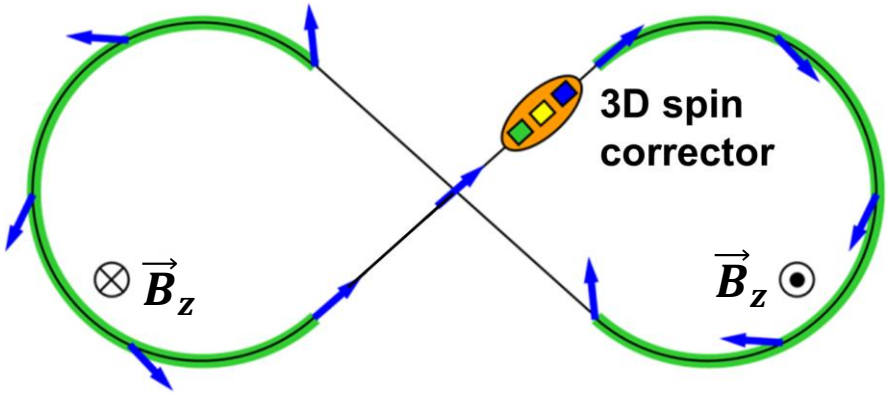
Spin-Transparent Ring Concept

- Storage ring with degenerate spin motion:
  - Spin transformation in one turn around ring is a unit operator, *i.e.*, no net spin rotation
  - Can be understood as spin-echo effect

- Figure-8 topology is most natural example:
  - Straightforward concept:
    spin rotation in one arc is compensated
    by spin rotation in second arc
  - No first-order spin chromaticity, compensation is energy independent
  - Originally proposed for polarized storage rings at JLEIC
  - Well-understood theory for magnetic rings:

    https://doi.org/10.1103/PhysRevLett.124.194801

    https://doi.org/10.3390/sym13030398

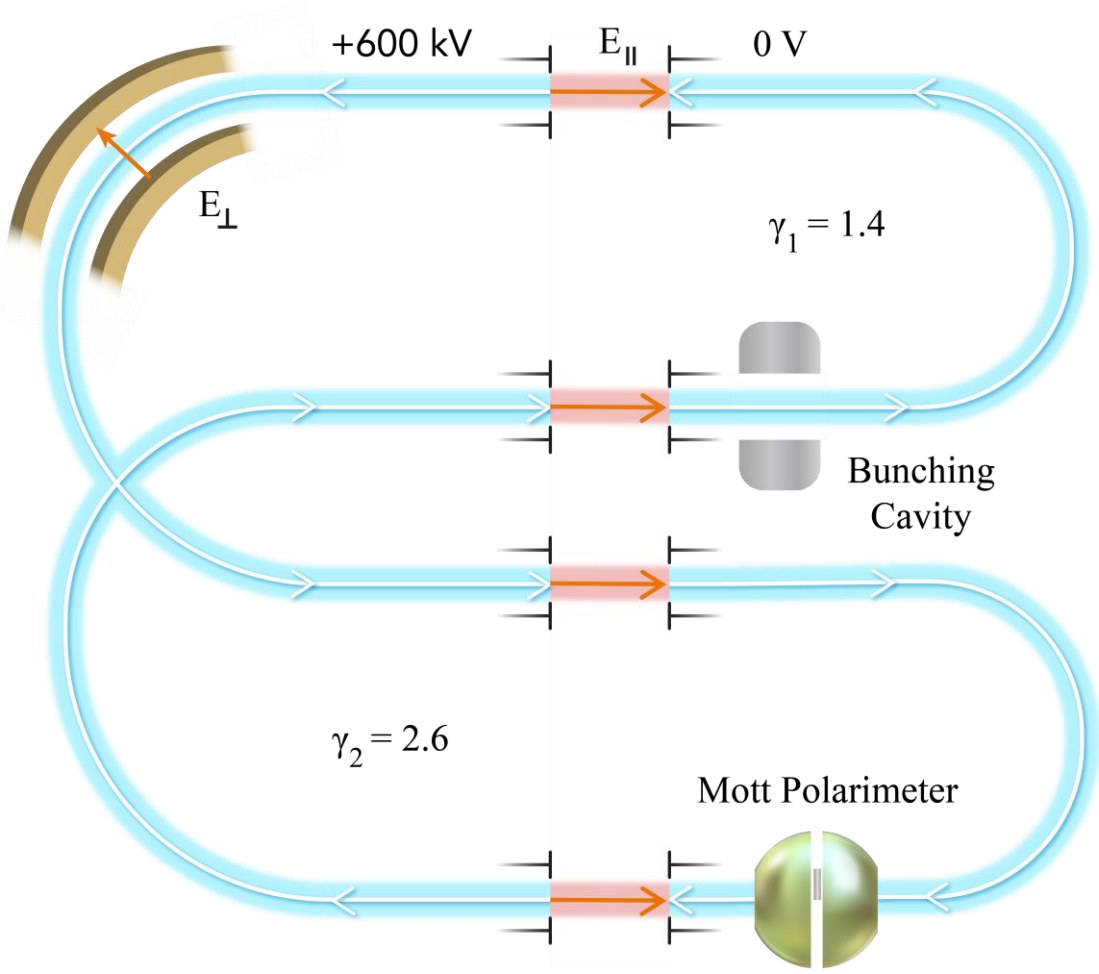


Reaching Spin Transparency in Real Ring

- Imperfections such as dipole roll and quad misalignment lead to closed orbit excursion and break spin degeneracy in a real-world ring
- Error effect is rather weak, spin sensitivity to errors can be described through spin response function based on linear optics
- Closed orbit excursion leads to coherent spin rotation, same for all particles
- Effect of imperfections can be experimentally measured and compensated by a local 3D spin rotator consisting of weak magnets, e.g., a sequence of alternating dipoles and solenoids can provide a rotation about an arbitrary axis cancelling error effect
- Higher-order incoherent spin rotations result from betatron and synchrotron motion and set a fundamental limit on Spin Coherence Time (SCT)

Measurement of Electric Dipole Moment (EDM) of Free Electron

- EDM is very sensitive to physics beyond Standard Model and new sources of Charge-conjugation and Parity (CP) violation – such CP violation could signal presence of new physics and explain puzzle of matter-antimatter asymmetry in Universe
- Current electron EDM upper limit ($d_e < 4.1 \times 10^{-30}$ e · cm) has been extracted from measurement using HfF^+ ions
- Any measurement of EDM relies on measuring spin precession rate in an electric field of a particle's rest frame, $\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}_{rest} + \vec{d} \times \vec{E}_{rest}$
- Magnetic Dipole Moment (MDM) effect is naturally suppressed at any energy due to spin-transparent ring topology and symmetry
- All-electric design with no magnetic fields to allow for two counter-rotating electron beams (CRA and CRB) to circulate concurrently – only one beam is shown in right figure
- EDM ring consists of two low-energy and two high-energy arcs connected by longitudinal static electric field sections – they preserve suppression of MDM effect but remove degeneracy of EDM spin precession

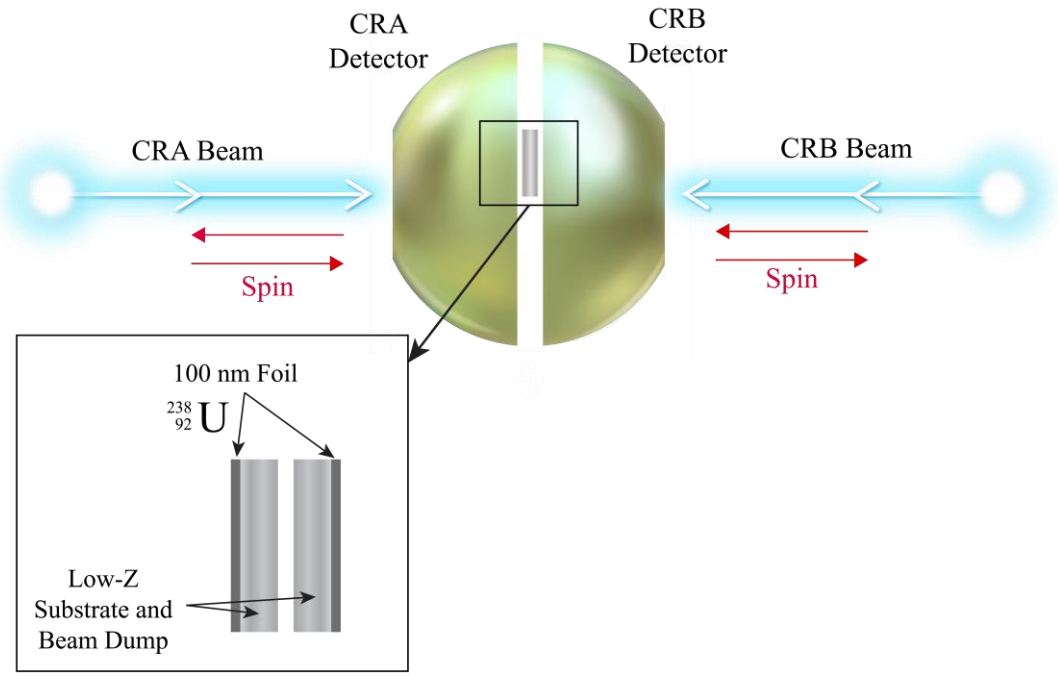


Mott Polarimeter

- Ring is filled with four polarized electron bunches, each 2 nC, in one direction and another four bunches, each 2 nC, in opposite direction
- Use half charge of each bunch to measure initial bunch polarization at t = 0 using a conventional Mott polarimeter
- Measure final bunch polarization at end of store time, t = SCT
- EDM results in a build-up of vertical component of beam polarization due to spin precession from longitudinal to vertical

Detector Coverage:

- $\varphi: 0 \rightarrow 2\pi$
- $\theta: 90° \rightarrow 160°$



Projected Electron EDM Statistical Limit

- Statistical uncertainty per fill:

$$\sigma_{EDM} = \sqrt{8}\frac{qs\hbar}{2m_e c}\frac{1}{\sqrt{N_e\,\epsilon}\,A_y\,P\,\Omega_{EDM}\,SCT}$$

$$2.5 \times 10^{-28}\ \text{e} \cdot \text{cm}$$

Electrons per Fill	N_e	$5.0 \cdot 10^{10}$
Polarimeter Efficiency	ϵ	0.0024
Analyzing Power	A_y	0.45
Beam Polarization	P	0.90
Spin rotation per η per time ($\eta = 6.0 \times 10^{-19}$)	Ω_{EDM}	0.45×10^{9} rad/s
Spin Coherence Time	SCT	1 day (86400 s)

- After five years of data taking, projected statistical limit is:

$$5.8 \times 10^{-30}\ \text{e} \cdot \text{cm}$$

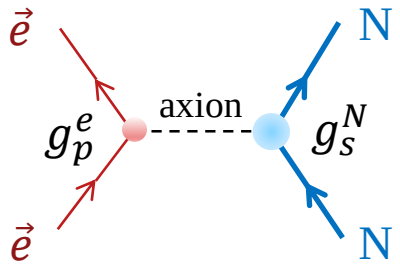
with expectation that further optimization and improvements will lower this limit

Sources of Systematic Uncertainties

- Both proton EDM collaborations have done extensive studies:
  - Many sources have been identified: background magnetic fields, vertical velocity, errors in construction and alignment, vertical E-field, …
  - Counter-rotating beams (and with both helicities) will suppress some uncertainties
  - Elaborate state-of-art shielding of background magnetic fields is practical since ring is very small but electron lighter mass (relative to proton) increases sensitivity to these fields
  - Store all polarization states (longitudinal, vertical, and radial) and with both helicities (positive and negative) at same time to control systematic uncertainties
- Mott Polarimetry related systematic uncertainties

Search for Axions

- Axions:
  - Axion is a new particle beyond Standard Model that can explain strong CP problem of Quantum Chromodynamics (QCD), so called “QCD axion” – no CP-violation has ever been seen in any experiment involving only strong interaction in spite of fact that Standard Model as a whole violates this symmetry
  - Axions are also a viable candidate for dark matter which dominates mass of Universe
- Search for axions:
  - Spin precession due to interaction of Milky Way’s dark matter axions with electrons: https://doi.org/10.1016/j.physletb.2023.138058
  - Spin precession due to axion-mediated nucleon-electron forces from Earth or test mass – next slide



- Spin-transparent storage rings:
  - Same as electron EDM ring, or
  - All-electric and one-energy (300 keV) ring – both MDM and EDM are suppressed

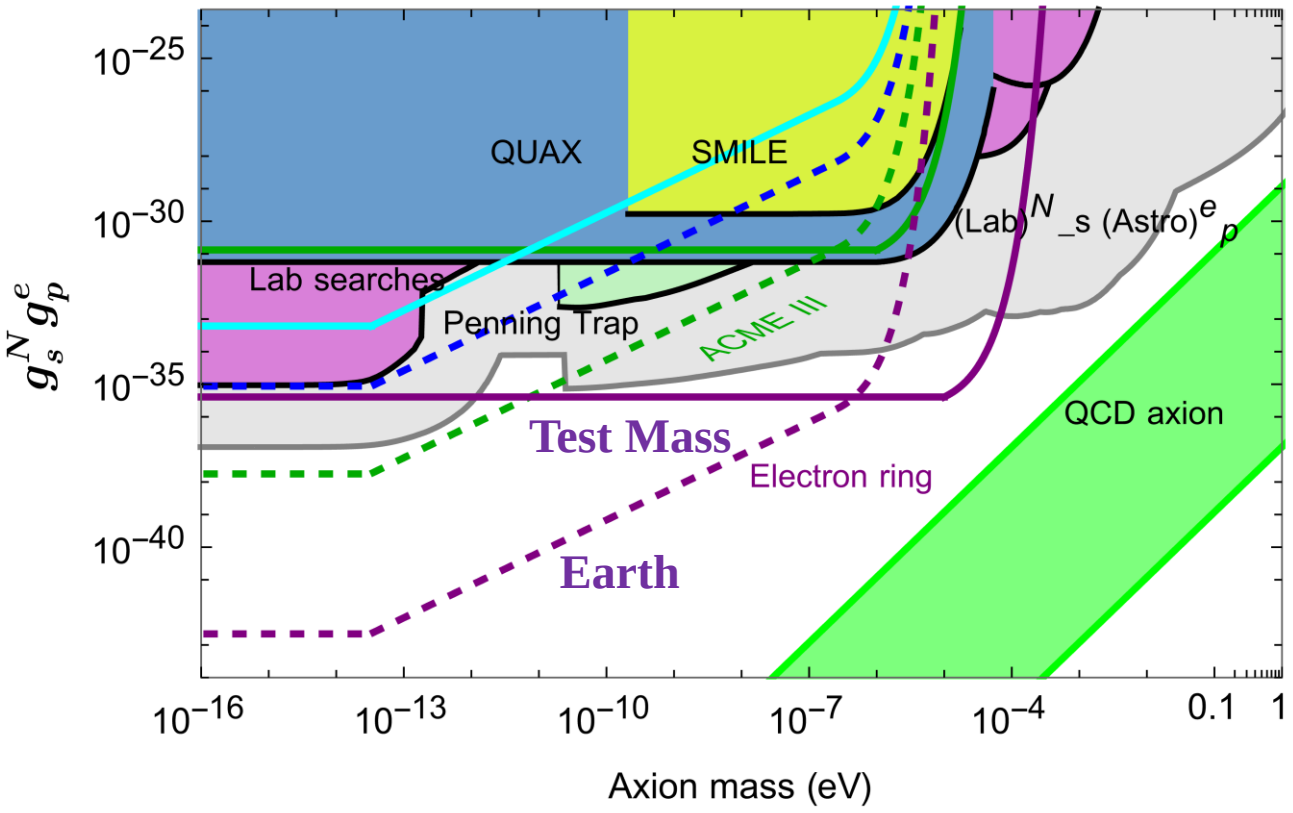
Experimental Bounds on Axion-mediated Forces

- Spin-transparent ring can measure nHz (10^{-9} Rad/s) spin precession frequency

- Axion sources:
  1. **Earth** – produces vertical axion coherent field
  2. **Test Mass** (e.g. lead bricks around ring) – produces radial axion coherent field

- Spin-transparent ring would surpass any existing or near-future search by several orders of magnitude

Xing Fan and Mario Reig,
https://doi.org/10.48550/arXiv.2310.18797
and private communication



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Summary

- Spin-transparent storage rings have many exciting applications: measurement of EDM of free electron and search for axions

- Presented new method for a direct measurement of $d_e = 5.8 \times 10^{-30}\ e \cdot cm$ and to search for axions using small rings in energy range below 1 MeV

- New method has following advantages:

  energy-independent spin tune, long SCT, any energy, minimum safety issues, straightforward polarimetry, counter-rotating beams, room-sized facility, manageable, low cost, and finally, such rings can serve as testbed for larger-scale experiments

- Concept could potentially be extended to low-energy polarized positron, proton, deuteron, and muon beams

Thank you

Measurement of EDM of Free Proton

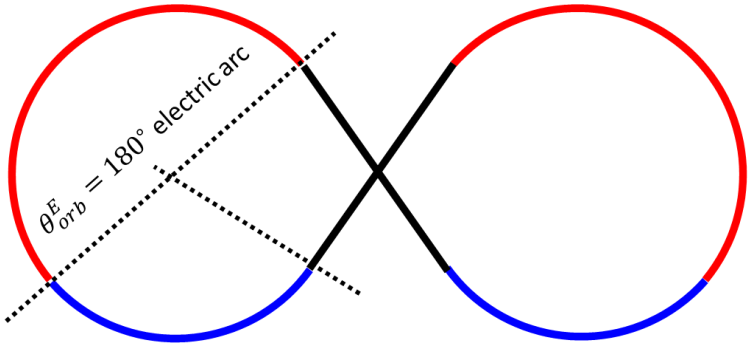
In collaboration with Bogdan Wojtsekhowski

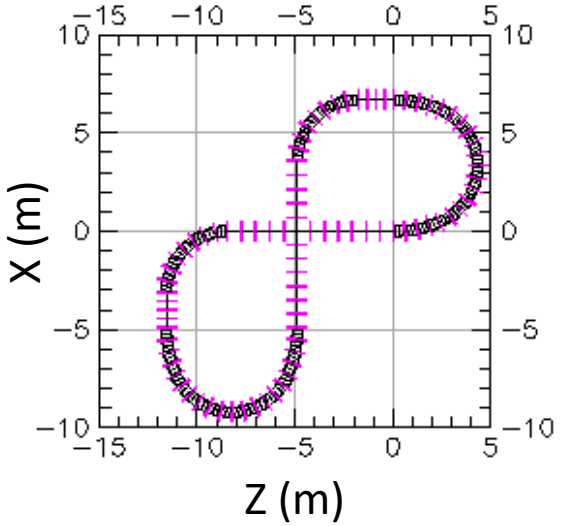
- Fully electric or magnetic figure-8 ring ⇒ Both MDM and EDM rotations suppressed
- **Alternating** electric and magnetic arcs in figure-8 ring ⇒ MDM suppressed, **EDM rotation is not!**
- EDM rotation

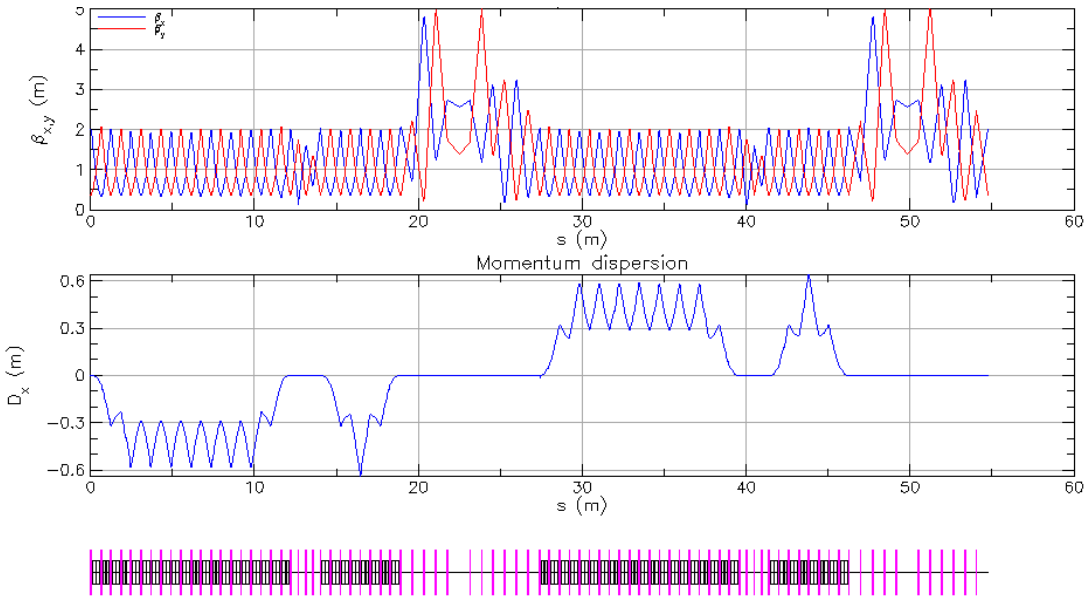
$$\frac{\partial|\psi|}{\partial N} = 4\left|\frac{\omega^E_{EDM}}{\omega^E_{MDM}} - \frac{\omega^B_{EDM}}{\omega^B_{MDM}}\right|\left|\sin\frac{\Theta_B}{2}\sin\frac{\Theta_E}{2}\right|$$

$$\frac{\omega^E_{EDM}}{\omega^E_{MDM}} = \frac{\eta}{2}\frac{\gamma^2\beta}{1-G\gamma^2\beta^2}, \qquad \frac{\omega^B_{EDM}}{\omega^B_{MDM}} = -\frac{\eta\beta}{2G}$$

$$\Theta_E = -\frac{1-G\gamma^2\beta^2}{\gamma}\theta^E_{orb}, \qquad \Theta_B = G\gamma\theta^B_{orb}$$







- $p = 100$ MeV/c, $d_p = 2\times10^{-27}$ e · cm ($\eta = 3.8\times10^{-13}$) ⇒ $\psi = 0.337\eta = 1.28\times10^{-13}$ rad/turn
- Extract signal through proton velocity dependence by measuring at several different β's:

$$\frac{\partial P}{\partial t} \propto C_1 G\beta + C_2\eta\beta^2 + C_3\beta^3$$

- Proton EDM can also be measured at magic energy (232.8 MeV) [arXiv:1912.07881, PhysRevD.105.032001]

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