Feasibility Study for an EDM Storage Ring

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on behalf of the CPEDM collaboration

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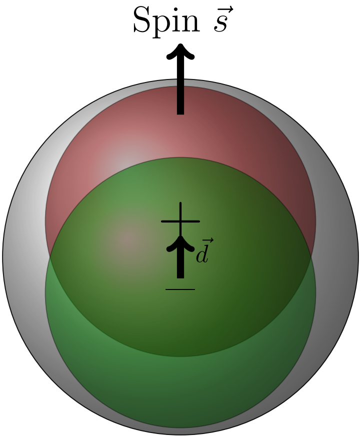
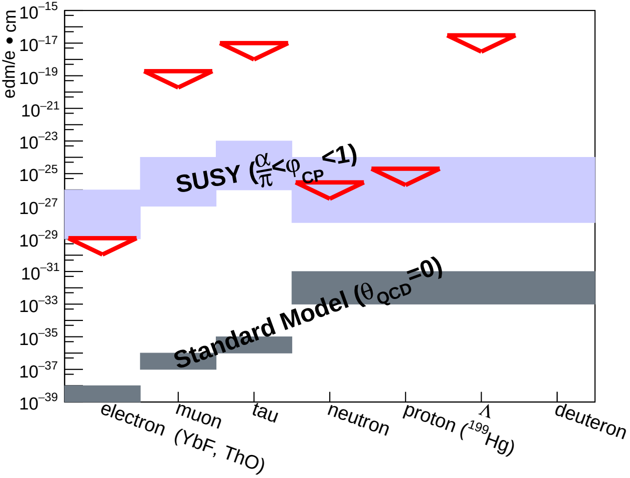
Electric Dipole Moments (EDM)

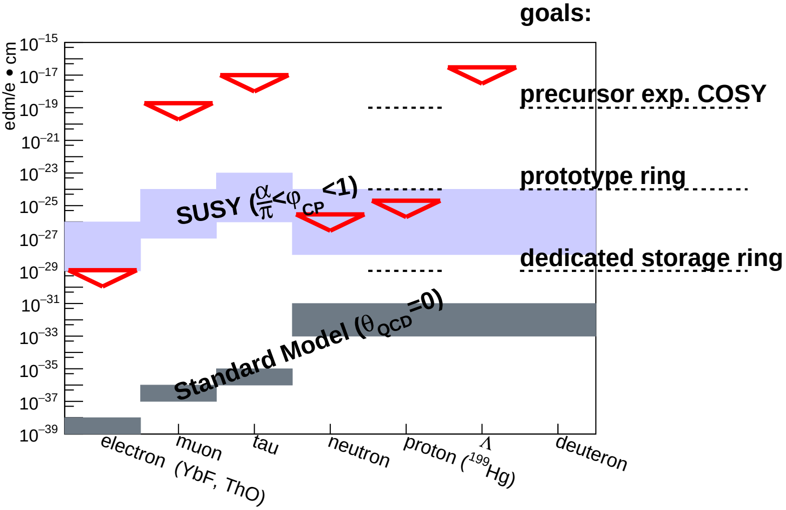


- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \stackrel{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to "matter-antimatter" asymmetry
- **axion** field leads to oscillating EDM

EDM: Current Upper Limits



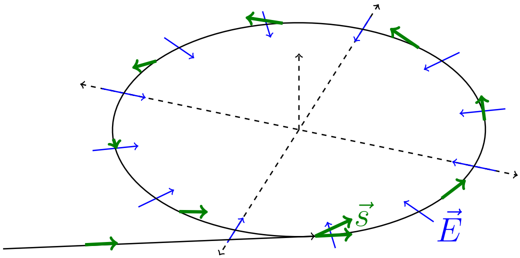
EDM: Current Upper Limits



our focus: EDMs of **charged** hadrons: p, d, ^{3}He

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, ...):
  Interaction of $\vec{d}$ with electric field $\vec{E}$
For charged particles: apply electric field in a storage ring:



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

In general:

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

build-up of vertical polarization $s_\perp \propto |d|$
if $\vec{s}_{\mathrm{horz}} || \vec{p}$ (**frozen spin**)

Requirements

Storage Ring (high precision, counter rotating beams, frozen spin, e.g. pure electric ring with magic $p = 0.701\mathrm{MeV}/c$)

beam intensity	$N = 4 \cdot 10^{10}$ per fill
polarization	$P = 0.8$
spin coherence time	$\tau = 1000\,\mathrm{s}$
electric fields	$E = 8\,\mathrm{MV/m}$
polarimeter analyzing power	$A = 0.6$
polarimeter efficiency	$f = 0.005$

$$\sigma_{\mathrm{stat}} \approx \frac{2\hbar}{\sqrt{Nf\tau}PAE} \quad \Rightarrow \sigma_{\mathrm{stat}}(1\mathrm{year}) = 2.4 \cdot 10^{-29}\, e\cdot\mathrm{cm}$$

challenge: get σ_{sys} to the same level

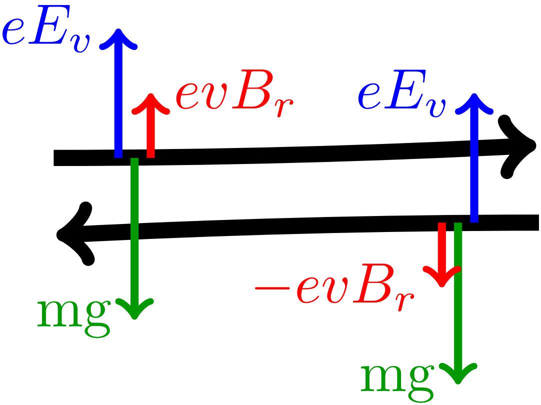
Systematics

Major source, radial magnetic field B_r:

- Difficulty: even tiny radial magnetic field, B_r, mimics EDM effect if :$\mu B_r \approx dE_r$
- order of magnitude: suppose $d = 10^{-29} e \cdot$cm in a field of $E_r = 10$MV/m.
  This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$

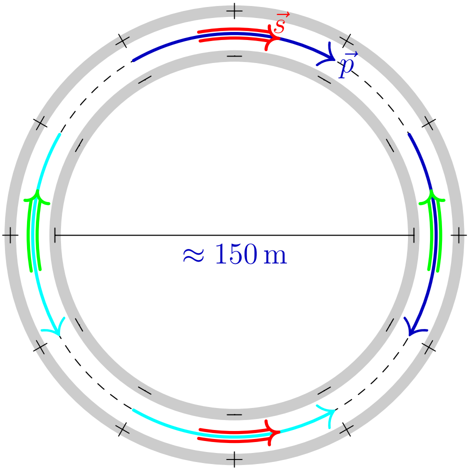
Solution: Use two beams running **clockwise** ↻ and **counter clockwise** ↺, separation of the two beams is sensitive to B_r

Systematics



Sensitivity needed: 5 pm (averaged, tune Q=0.1)
open questions: number/position of beam position monitors (BPM), phase space, intensity differences of the two beams

Electric Storage Ring



- 500 m electro static ring (largest ever built) with counter-rotating beams
- many systematic effects cancel because of ↻ and ↺ beams (at the same time and the same orbit)

Difficult to design and build in one step ⇒ **staged approach**

Staged approach

Stage 1

precursor experiment

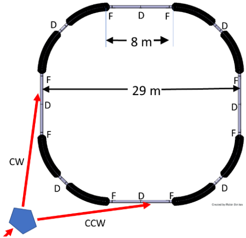
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

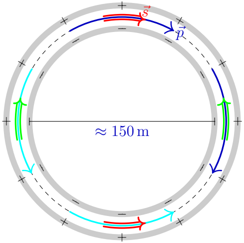


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3

dedicated storage ring



- magic momentum

(701 MeV/c)

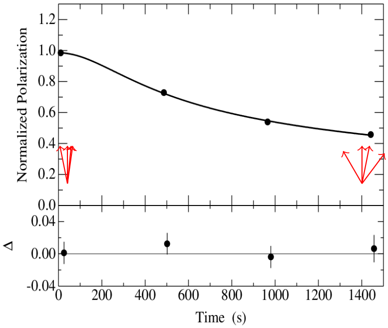
10 years

$\sigma_{EDM}/(e \cdot \mathrm{cm})$

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-2}

Stage 1: Precursor Experiment

- Ongoing at COSY/ Forschungszentrum Jülich
- Achievements:
  - Long Spin Coherence time > 1000 s ✓

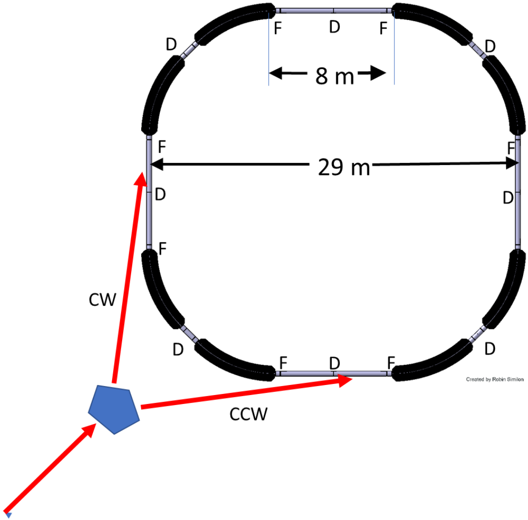


  - measurement and manipulation and polarisation vector ✓
- First deuteron EDM measurement underway

Step 2: Prototype Ring

- operate electrostatic ring
- store 10^{10} particles for 1000 s
- simultaneous ↻ and ↺ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies:
  beam cooling, deflector, beam position monitors, shielding
  …
- perform EDM measurement

Ring Lattice & Bending Element



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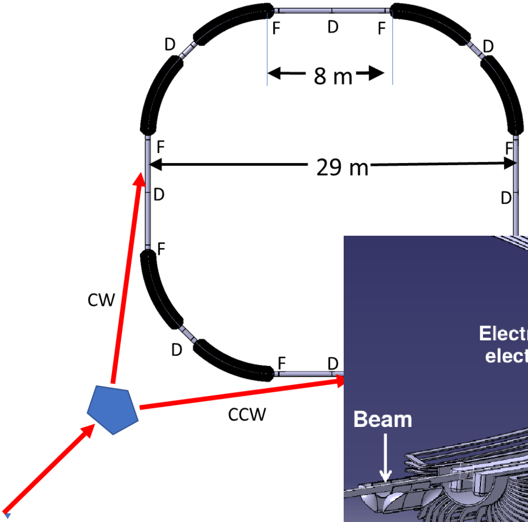
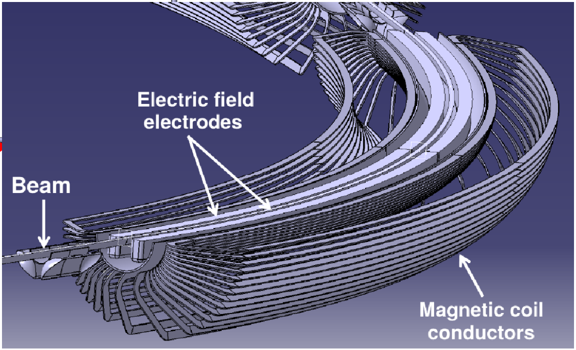




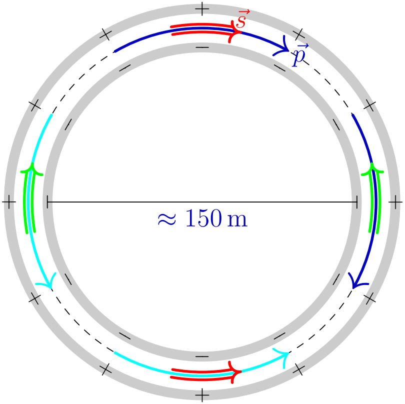
Parameters and costs

	E only	$E \times B$	unit
kinetic energy (momentum)	30 (239)	45 (294)	MeV, (MeV/c)
$\beta = v/c$	0.247	0.299	
momentum	239	294	MeV/c
magnetic rigidity $B\rho$	0.798	0.981	T·m
electric rigidity $E\rho$	59.071	87.941	MV
γ (kinetic)	1.032	1.048	
emittance $\epsilon_x = \epsilon_y$	1.0	1.0	mm·mrad
acceptance $a_x = a_y$	1.0	10.0	mm·mrad

Costs: $\approx$ 17 M€(ring only)

Step 3: Dedicated Ring

- pure electric ring:
  frozen spin ($p = 701$ MeV/c E_{kin}=233 MeV):



- other options discussed:
  hybrid ring (use $\vec{B}$ field for focusing), doubly magic ring (store two species of particles)

Summary

- EDMs are unique probe to search for new CP-violating interactions (and contribute to axion searches)
- **charged** particle EDMs can be measured in storage rings
- step wise approach:

precursor at COSY $\rightarrow$ prototype (100 m) $\rightarrow$ dedicated ring (500 m)

Document submitted to ESPP in Dec. 2018 (arXiv:1812.08535)

Spare

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})\right] \times \vec{s}$$

$$\vec{d} = \eta \frac{q}{2m}\vec{s}, \quad \vec{\mu} = 2(G + 1)\frac{q}{2m}\vec{s}$$

BMT: Bargmann, Michel, Telegdi

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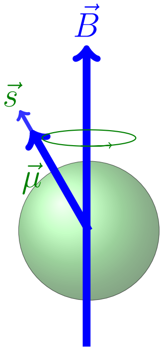

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	☺	☹
1.) pure electric ring	no $\vec{B}$ field needed, CW/CCW beams simultaneously	works only for particles with $G > 0$ (e.g. p)
2.) combined ring	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$ required
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G, i.e. no **frozen spin**

ideal: suppress precession due to magnetic dipole moment (**frozen spin**)

$$\vec{d} = \eta \frac{q}{2m}\vec{s}, \quad \vec{\mu} = 2(G+1)\frac{q}{2m}\vec{s}$$

BMT: Bargmann, Michel, Telegdi

EDM activities around the world

Neutrons: (~ 200 ppl.)

- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

Storage rings: (~ 400 ppl.)

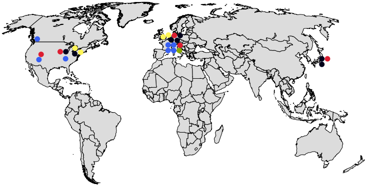
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

High Energy Physics: (~ 20 ppl.)

- Λ-baryon @ LHCb

Atoms: (~ 60 ppl.)

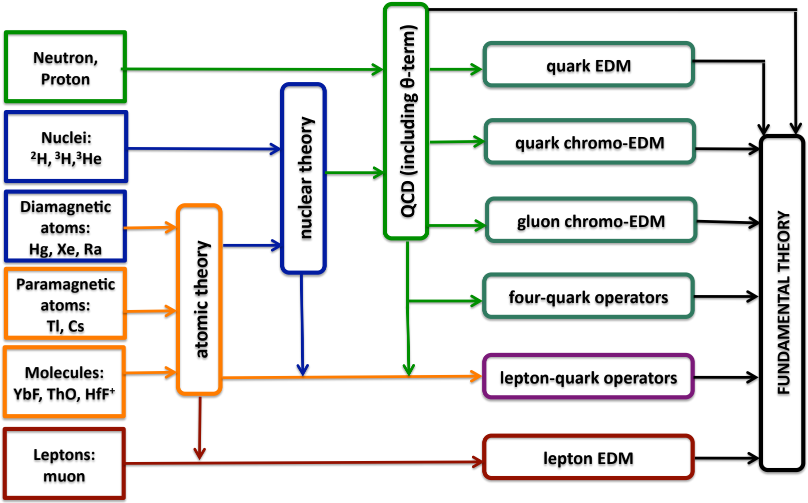
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken



Molecules: (~ 55 ppl.)

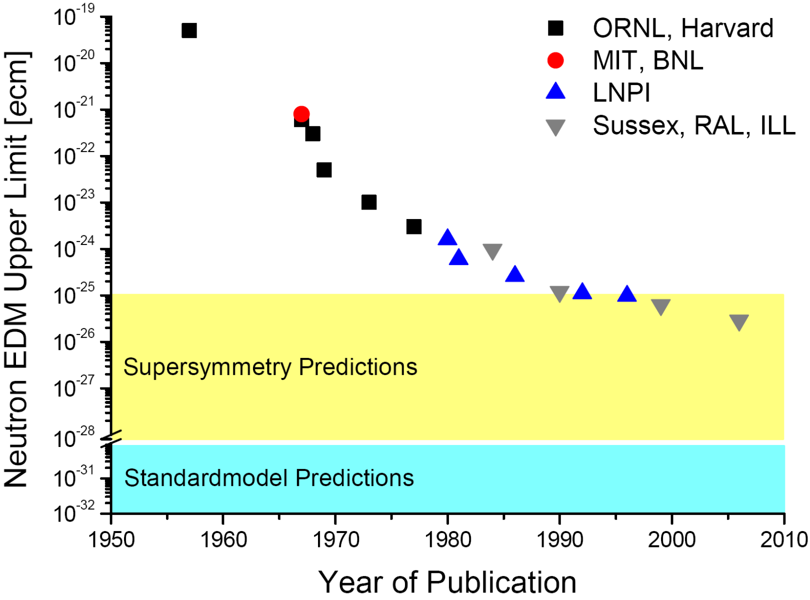
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhe
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

Why Charged Particle EDMs?



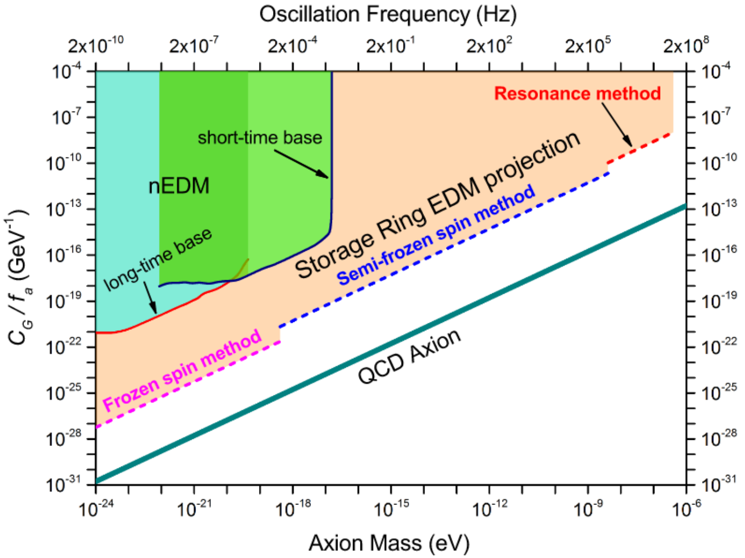
J. de Vries

Neutron EDM



Neutron EDM Upper Limit [ecm]
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
10^-27
10^-28
10^-31
10^-32
ORNL, Harvard
MIT, BNL
LNPI
Sussex, RAL, ILL
Supersymmetry Predictions
Standardmodel Predictions
1950
1960
1970
1980
1990
2000
2010
Year of Publication

Axion Searches



S. P. Chang, S. Haciomeroglu, O. Kim, S. Lee, S. Park and Y. K. Semertzidis, PoS PSTP **2017** (2018) 036