# Electric Dipole Moment Measurements at Storage Rings

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Spin 2021, October 2021

# Outline

- **Motivation**
  EDMs and their relation to CP violation and Matter- Antimatter - asymmetry in the universe
- **Experimental Method**
  Spin Motion in Storage Rings
- **Experimental Results & Plans**
  with focus on activities at Cooler Synchrotron COSY, Germany and EDM prototype ring

# Motivation

# 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 $\mathcal{T} \overset{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to matter-antimatter asymmetry
- axion field leads to oscillating EDM

talks on EDM theory:

40 74 114 122 167

# Proton EDM

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

## *N* BARYONS
## ($S = 0$, $I = 1/2$)

$p$, $N^+ = uud$; $n$, $N^0 = udd$

### *p*

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646663 \pm 0.00000000009$ u (S = 2.9)
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008$ $\mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0.002 \pm 0.004) \times 10^{-6}$
Electric dipole moment $d < 0.021 \times 10^{-23}$ $e$ cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm$^3$
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm$^3$ (S = 1.2)
Charge radius, $\mu p$ Lamb shift = $0.84087 \pm 0.00039$ fm [d]
Charge radius = $0.8409 \pm 0.0004$ fm [d]
Magnetic radius = $0.851 \pm 0.026$ fm [e]
Mean life $\tau > 3.6 \times 10^{29}$ years, CL = 90% [f] ($p \rightarrow$ invisible mode)
Mean life $\tau > 10^{31}$ to $10^{33}$ years [f] (mode dependent)

# EDM: Current Upper Limits

storage rings: EDMs of **charged** hadrons: $p$, $d$, $^3$He, goal: $10^{-29}\,e\,$cm precision

more non-storage ring EDM talks:

nEDM: 38 60 62, atoms/molecules: 138, 179

# Experimental Method

# Experimental Method: Generic Idea

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \underbrace{d(\vec{E} + \vec{v} \times \vec{B})}_{=\vec{\Omega}_{\mathrm{EDM}}} \times \vec{s}$$

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

# Experimental Method: Generic Idea

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \underbrace{d(\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}} \times \vec{s}$$

In general:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}) \times \vec{s}$$

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

# Spin Precession: Thomas-BMT Equation

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

electric dipole moment (EDM): $\vec{d} = \eta \frac{q\hbar}{2mc}\vec{s}$ ,

magnetic dipole moment (MDM): $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$

Note: $\eta = 2 \cdot 10^{-15}$ for $d = 10^{-29}$ecm, $G \approx 1.79$ for protons

# Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\vec{\Omega}_{\mathrm{MDM}} = 0\,,\quad \textbf{frozen spin}} + \underbrace{\frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}}\right] \times \vec{s}$$

frozen spin achievable with pure electric field if $G = \frac{1}{\gamma^2 - 1}$,

works only for $G > 0$, e.g. proton

or with special combination of $E$, $B$ fields and $\gamma$, i.e. momentum

# Momentum and ring radius for proton in frozen spin condition

Two options:

- Pure electric ring:
  $p = 707$MeV, bending radius$\approx$ 50 m at $E$=8 MV/m

- ⋆ combined prototype ring:
  $p = 300$MeV, bending radius$\approx$ 9 m at $E$=7 MV/m

# Different Options

| | ☺ | ☹ |
|---|---|---|
| 3.) pure electric ring | no $\vec{B}$ field needed, $\circlearrowleft$, $\circlearrowright$ beams simultaneously | works only for particles with $G > 0$ (e.g. $e, p$) |
| 2.) combined ring | works for $e, p, d$, $^3$He, smaller ring radius | both $\vec{E}$ and $\vec{B}$ $B$ field reversal for $\circlearrowleft$, $\circlearrowright$ required |
| 1.) pure magnetic ring | existing (upgraded) COSY ring can be used, running now | lower sensitivity, precession due to $G$, i.e. no **frozen spin** |

# Staged approach

precursor experiment

at Cooler Synchrotron COSY

- magnetic storage ring

now

prototype ring

- initially electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

dedicated storage ring

- magic momentum

(701 MeV/$c$)

10 years

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

$10^{-17}$ $10^{-18}$ $10^{-19}$ $10^{-20}$ $10^{-21}$ $10^{-22}$ $10^{-23}$ $10^{-24}$ $10^{-25}$ $10^{-26}$ $10^{-27}$ $10^{-28}$ $10^{-29}$

# Precursor Experiment

| | |
|---|---|
| COSY circumference | 183 m |
| deuteron momentum | 0.970 GeV/$c$ |
| $\beta(\gamma)$ | 0.459 (1.126) |
| magnetic anomaly $G$ | $\approx -0.143$ |
| revolution frequency $f_{\text{rev}}$ | 752543 Hz |
| cycle length | 100-1500 s |
| nb. of stored particles/cycle | $\approx 10^9$ |

JEDI collaboration,

# Results & Plans

# Observation of polarization build-up

- radio-frequency Wien filter (WF) provides partially frozen spin
- polarization build-up proportional to EDM . . . and many perturbations
- perturbations are under investigation

More details in:

37 63 71 79 89

# Precursor Experiment at COSY

Tools developed to manipulate and measure beam polarization:

- reaching $>$ 1000 s spin coherence time
- measure 120 kHz spin tune precession in horizontal plane to $10^{-10}$ in 100 s
- development of polarization feed back system
- $\Rightarrow$ **Single bunch spin manipulation**

# Principle of storage ring axion experiment

- Axion field gives rise to an effective time-dependent $\theta$-QCD term
- This gives rise to an oscillating electric dipole moment EDM $d$.

$$d = d_{DC} + d_{AC} \sin(\omega_a t + \varphi_a)$$

$$\omega_a = \frac{m_a c^2}{\hbar}$$

# First Results

- Momentum scan $\rightarrow \Omega_{MDM}$ scan $\rightarrow$ axion mass scan
- mass range covered: $4.96 - 5.02 \cdot 10^{-9}$ eV
- axion would show up as jump in vertical polarisation
- allows to search at a given mass

# Prototype Ring: Lattice & Bending Element

- operate electrostatic ring
- store $10^9 - 10^{10}$ 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

45 68 204

# Prototype Ring: Lattice & Bending Element

CPEDM collaboration,
CERN Yellow report
https://doi.org/10.23731/CYRM-2021-003;

# (Almost pure) Electric storage ring

- Electric bends
- Uses **magnetic** focusing
  $\rightarrow$ reduction of systematic error due to radial magnetic field
- bending radius = 95 m

US based storage ring
EDM collaboration
arXiv:2007.10332v2

# Electron & muon EDM

50. **Electron EDM** @ Jefferson Lab
    smaller ring size (few meters) using spin transparent mode
    R. Suleiman, EDM in Small Rings, 21 Oct 2021, 08:10
    see also:
81. Yury Filatov, Spin Transparency Method for High Precision Experiments with Polarized Beams, 19/10/2021, 20:30
41. **muon EDM** @ PSI
    dedicated experiment to measure muon EDM
    Mikio Sakurai: Towards a search for the muon electric dipole moment at PSI using the frozen-spin technique, 19/10/2021, 21:00
127. **muon EDM** @ JPARC
    Yusuke Takeuchi, Muon g-2/EDM Experiment at J-PARC, 20/10/2021, 11:45
130. **muon EDM** @ FNAL muon EDM measurement parallel to muon $g-2$ measurement
    V. Tishchenko, Measurement of muon $g-2$, 18 Oct 2021, 15:30

# Other talks related to storage ring EDM I

- Experiments at COSY
  37. Max Vitz - Orbit Response Matrix Analysis for COSY - Model Optimization using LOCO, 18/10/2021, 21:20
  63. Artem Saleev - Spin tune response to vertical orbit correction at COSY
  71. Tim Wagner - Beam-based alignment at the Cooler Synchrotron (COSY), 19/10/2021, 21:20
  79. Vera Shmakova - The search for electric dipole moments of charged particles using storage rings, 19/10/2021, 20:30
  89. Jamal Slim - Towards a surrogate computational tool to quantify the systematic uncertainties in EDM experiments in storage rings, 19/10/2021, 21:20
- Prototype Ring
  45. Otari Javakhishvili - Pellet target development for storage ring EDM polarimetry 19/10/2021, 21:00
  68. Saad Siddique - Simulations of Beam Dynamics and Beam Lifetime for the Prototype EDM Ring 18/10/2021, 21:00
  204. Rahul Shankar - Optimisation of spin-coherence time in a prototype storage ring for electric dipole moment measurements

# 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
- Several projects are ongoing on to search for $e^-$, $\mu$, $p$, $d$ EDM

European Research Council

# Extra Slides

# Axion Searches at storage rings

https://doi.org/10.1140/epjc/s10052-020-7664-9

# Momentum and ring radius for **proton** in frozen spin condition

$G = 1.7928474$

# Momentum and ring radius for **deuteron** in frozen spin condition

$G = -0.1425617689$

# Momentum and ring radius for **electron** in frozen spin condition

$G = 0.001159652$

# Statistical Sensitivity

| | |
|---|---|
| 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 $\sigma_{\mathrm{sys}}$ to the same level

# Systematic Sensitivity

signal: $\Omega_{\mathrm{EDM}} = \frac{dE}{s\hbar} = 2.4 \cdot 10^{-9}\,\mathrm{s}^{-1}$ for $d = 10^{-29} e\,\mathrm{cm}$

- radial $B$-field of $B_r = 10^{-17}\,\mathrm{T}$:
  $\Omega_{B_r} = \frac{eGB_r}{m} = 1.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$
- geometric Phases (non-commutation of rotations), $B_{\mathrm{long}}, B_{\mathrm{vert}} \approx 1\mathrm{nT}$
  $\Omega_{\mathrm{GP}} = \left(\frac{eGB}{16m}\right)^2 \frac{1}{f_{\mathrm{rev}}} = 3.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$
- General Relativity:
  $\Omega_{\mathrm{GR}} = -\frac{\gamma}{\gamma^2+1}\frac{\beta g}{c} = -4.4 \cdot 10^{-8}\mathrm{s}^{-1}$
- ...

# Systematic Sensitivity

Remedy:

$$\begin{aligned} \circlearrowright: \quad \Omega_{\mathrm{CW}} &= \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}} + \Omega_{B_r} \,, \\ \circlearrowleft: \quad \Omega_{\mathrm{CCW}} &= \Omega_{\mathrm{EDM}} - \Omega_{\mathrm{GP}} - \Omega_{\mathrm{GR}} + \Omega_{B_r} \,. \end{aligned}$$

$\Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}}$ drops out in sum, $\Omega_{\mathrm{CW}} + \Omega_{\mathrm{CCW}}$, effect of $B_r$ can be subtracted by observing displacement of the two beams.

Conclusion:

Statistically one can reach sensitivity of $\approx 10^{-29} e\,\mathrm{cm}$, many systematic effects can be controlled using $\circlearrowleft$ and $\circlearrowright$ beams, needs further investigation
$\rightarrow$ **staged approach**

# Systematics

# Systematics