Search for electric dipole moments of charged particles in storage rings

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Motivation
Introduction

Electric Dipole Moments (EDM)

- Permanent separation of + and - charge
- Fundamental property of particles (like magnetic moment, mass, charge)
- Possible only via violation of time-reversal $T \overset{CPT}{=} CP$ and parity $P$
- Nothing to do with EDMs of molecules (e.g. $H_2O$)
- Connection to matter-antimatter asymmetry
Symmetry violations

T and P violation of EDM

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

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

EDM meas. test violation of P and T symmetries (\( CPT \cong CP \))
Symmetry violations

**CP-violation & Matter-Antimatter Asymmetry**

- **Matter dominance:** Excess of Matter in the Universe:
  
  \[
  \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}
  \]

<table>
<thead>
<tr>
<th>observed</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6 \times 10^{-10}$</td>
<td>$10^{-18}$</td>
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- Sacharov (1967): CP-violation needed for baryogenesis

  \[\Rightarrow\] New CP-V sources beyond SM needed
- Could show up in EDMs of elementary particles
Symmetry violations

**CP-violation & connection to EDMs**

<table>
<thead>
<tr>
<th>Weak interaction</th>
<th>Strong interaction</th>
<th>beyond Standard Model</th>
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</thead>
<tbody>
<tr>
<td>CKM matrix</td>
<td>$\theta_{QCD}$</td>
<td>e.g. SUSY</td>
</tr>
<tr>
<td>→ unobservably small EDMs</td>
<td>→ best limit from neutron EDM</td>
<td>→ accessible by EDM measurements</td>
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EDM: Current upper limits

FZ Jülich: EDMs of charged hadrons: $p, d, {^3He}$
Why Charged Particle EDMs?

- No direct measurement for charged hadron EDMs
- Potentially higher sensitivity (compared to neutrons):
  - longer lifetime;
  - more stored protons/deuterons
  - can apply larger electric fields in storage rings
- complementary to neutron EDM:
  
  EDM of single particle not sufficient to identify CP-V source
Sources of CP Violation

- Neutron, Proton
- Nuclei: $^2\text{H}$, $^3\text{H}$, $^3\text{He}$
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: Ti, Cs
- Molecules: YbF, ThO, HfF$^+$
- Leptons: muon

QCD (including $\theta$-term)
- quark EDM
- quark chromo-EDM
- gluon chromo-EDM
- four-quark operators
- lepton-quark operators
- lepton EDM

atomic theory

nuclear theory

J. de Vries
Experimental method
Search for EDM in storage rings: concept

**Procedure**

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

\[ \vec{\omega}_a = 0 \]
\[ \frac{ds}{dt} = \vec{d} \times \vec{E} \]
\[ ds/dt = d \times E \]
Spin Precession in a storage ring

**Thomas-BMT equation**

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

- Mag. dip. mom. (MDM): \( \vec{\mu} = 2(G + 1) \frac{q\hbar}{2m} \vec{s} \) (G=1.79 for proton)
- El. dip. mom. (EDM): \( \vec{d} = \eta \frac{q\hbar}{2mc} \vec{s} \) (\( \eta = 2 \cdot 10^{-15} \) for d= 10\(^{-29}\) e · cm)

**Frozen spin**

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

- Achievable with pure electric field for proton (G>0): \( G = \frac{1}{\gamma^2 - 1} \)
- Requires special combination of E, B fields and \( \gamma \) for d, \(^3\)He (G<0)
Requirements and expectation

Requirements

High precision, primarily electric storage ring

- **Crucial role** of alignment, stability, field homogeneity and shielding from magnetic fields.
- High beam intensity: $N = 4 \cdot 10^{10}$ per fill
- Polarized hadron beams: $P = 0.8$
- Long spin coherence time: $\tau = 1000$ s
- Large electric fields: $E = 10$ MV/m
- Efficient polarimetry with:
  - large analyzing power: $A = 0.6$
  - high efficiency detection: eff. $= 0.005$

Expected statistical sensitivity in 1 year of DT:

- $\sigma_{\text{stat}} = \frac{h}{\sqrt{Nf\tau PAE}} \Rightarrow \sigma_{\text{stat}} = 10^{-29} e \cdot cm$

- Experimentalist’s goal: provide $\sigma_{\text{syst}}$ to the same level.
Systematics

**Example: radial B field \((B_r)\)**

- \(B_r\) can mimic EDM (if \(dE_r \approx \mu B_r\))
- E.g. \(d = 10^{-29} \text{ e} \cdot \text{cm}, E_r = 10 \text{ MV/m}\)
  - Corresponds to \(B_r = \frac{dE_r}{\mu} \approx 10^{-17} \text{T}\)

**Solution**

- Use of two beams running clockwise and counterclockwise
- Separation of the two beams sensitive to \(B_r\)
Achievements at COSY
The COSY storage ring at FZ-Jülich (Germany)

COoler SYnchrotron COSY
- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta $p = 0.3$-$3.7$ GeV/c
- Phase-space cooled internal and extracted beams

Formerly used as spin-physics machine for hadr. physics:
- Ideal starting point for srEDM related R&D
- First direct measurement of deuteron EDM
Experiment preparation

1. Inject and accelerate vertically pol. deut. to $p \approx 1 \text{ GeV/c}$
2. Flip spin with solenoid into horizontal plane
3. Extract beam slowly (100 s) on target
4. Measure asymmetry and determine spin precession
Polarimeter

- Elastic deuteron-carbon scattering
- Up/Down asymmetry \( \propto \) horizontal polarization \( \rightarrow \nu_s = \gamma G \)
- Left/Right asymmetry \( \propto \) vertical polarization \( \rightarrow d \)

Deuteron at p = 1GeV/c: \( \gamma = 1.13 \) and \( \nu_s = \gamma G \simeq -0.161 \)

Spin-dependent differential cross section:
\[
N_{up,down} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\nu_s \omega_{rev} t), \quad f_{rev} = 781 \text{ kHz}
\]
Asymmetry: $\epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = p_z A_y \sin (2\pi \cdot \nu_s \cdot n_{\text{turns}})$

**Challenge**

- Spin precession frequency: 126 kHz
- $\nu_s = 0.16 \rightarrow 6$ turns/precession
- Event rate: $5000 \text{ s}^{-1} \rightarrow 1$ hit / 25 precessions $\rightarrow$ no direct fit of rates

**Solution: map many event to one cycle**

- Counting turn number $n \rightarrow$ phase advance $\phi_s = 2\pi \nu_s n$
- For intervals of $\Delta n = 10^6$ turns: $\phi_s \rightarrow \phi_s \mod 2\pi$
Achievements

**Optimization of spin-coherence time**

2012: **First result**

Exp. decay of asymmetry:

\[ \epsilon_{UD} = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)} \]

\[ \tau_{SCT} \approx 20 \text{ s} \]

\[ \chi^2 / \text{ndf} = 69.29 / 90 \]

Amplitude: 0.282 ± 0.006

- \[ \frac{1}{\tau_{SCT}} = -0.04968 \pm 0.00145 \]

2013: **improvement**

Use of 6-pole magnets to correct higher order effects:

spin-coherence time increased

\[ \tau_{SCT} \approx 400 \text{ s} \]

\[ \chi^2 / \text{ndf} = 93.9 / 90 \]

Amplitude: 0.2667 ± 0.0016

- \[ \frac{1}{\tau_{SCT}} = -0.002028 \pm 0.000149 \]
Achievements

Optimization of spin-coherence time

More recent progress on $\tau_{SCT}$

- $\tau_{SCT} = (782 \pm 117)\text{s}$
- Previously: $\tau_{SCT}^{(\text{VEPP})} \approx 0.5$ s
  ($\approx 10^7$ spin revolutions)
Achievements

Optimization of spin-coherence time

![Graph showing the optimization of spin-coherence time](image)

- More recent progress on \( \tau_{SCT} \):
  - \( \tau_{SCT} = (782 \pm 117) \text{s} \)
  - Previously: \( \tau_{SCT} (\text{VEPP}) \approx 0.5 \text{ s} \) 
    \( \approx 10^7 \text{ spin revolutions} \)

Major achievement:
- About \( 10^9 \) stored deuterons.
- Long SCT was one of main obstacles of srEDM experiments.
- Large value of SCT of crucial importance, since \( \sigma_{\text{STAT}} \propto \frac{1}{\tau_{SCT}} \)
Spin-tune

\[ \nu_s = \gamma G = \frac{\text{nb.spin–rotations}}{\text{nb.particle–revolutions}} \]

Achievements

Stored deuterons at COSY

- \( p_d = 1 \text{ GeV/c (}\gamma=1.13) \), \( G=-0.1425 \) \( \Rightarrow \nu_s = \gamma G \approx -0.161 \)
- \( f_{\text{rev}} = 781 \text{ kHz} \) \( \Rightarrow \nu_s = \nu_s \times f_{\text{rev}} \approx 126 \text{ kHz} \)
Precise determination of the spin-tune

**Time stamping of events:**
- Monitor phase of asymm. with fixed $\nu_s$ in 100 s:
  - $\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi} \frac{d\tilde{\phi}}{dn} = \nu_s^{\text{fix}} + \Delta \nu_s(n)$

**Experimental result:**
- Interpolated spin tune in 100 s:
  - $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta \nu_s/\nu_s \approx 10^{-10}$)
  - Angle precision: $2\pi \times 10^{-10} = 0.6$ nrad
  - Previous best: $3 \times 10^{-8}$ per year (g-2 experiment)

→ new tool to study systematic effects in storage rings
Phase locking spin precession in machine to device RF

At COSY: freezing of spin precession not possible

→ phase-locking required to achieve precision for EDM

Spin-feedback system maintains:
- resonance frequency
- phase between spin-precession and device RF

Major achievement:
Error of phase-lock $\sigma_\phi = 0.21$ rad
Achievements

Study of machine imperfections

Precise experimental technique

New method to investigate magnetic machine imperfections through accurate determination of spin-tune

Spin tune mapping

- Two solenoids act as spin rotators → generate artificial imperfection fields
- Measure spin-tune shifts vs spin kicks

- Saddle point determines tilt of stable spin axis by machine imperfections
- Control of background from MDM: \( \Delta c = 2.8 \times 10^{-6} \) rad
- Systematics sensitivity for d-EDM: \( \sigma_d \approx 10^{-20} \) e·cm
Other technological developments
Achievements

E/B deflector development using small-scale setup

- Polished stainless steel
  - 240 MV/m at 0.05 mm with half-sphere facing flat surface
  - 17 MV/m with 1 kV at 1 mm with two small half-spheres
- Polished aluminum
  - 30 MV/m at 0.1 mm using two small half-spheres
- TiN coating
  - Smaller breakdown voltage
  - Zero dark current
Achievements

**Dark current measurements**

**Dark current stainless-steel half-sphere electr. (R=10 mm)**

- Distances $S = 1$, $0.5$ and $0.1$ mm where:

  $$E_{\text{max}} = \frac{U}{S} \cdot F,$$

  where

  $$F = \frac{1}{4} \left[ 1 + \frac{S}{R} + \sqrt{\left(1 + \frac{S}{R}\right)^2 + 8}\right]$$

![Graph showing dark current measurements](image)

Promising → tests with real size deflector elements required
E/B deflector development using real-scale setup

**Equipment**
- Dipole magnet $B_{\text{max}} = 1.6$ T
- Mass = 64 t
- Gap height = 200 mm
- Protection foil between chamber wall and detector

**Parameters**
- Electr. length = 1020 mm
- Electr. height = 90 mm
- Electr. spacing = 20 to 80 mm
- Max potential = $\pm 200$ kV
- Material: Al coated with TiN

- First results expected soon
## Achievements

**Beam position monitors for srEDM experiments**

### Development of compact BPM based on Rogowski coil

- **Main adv.**: short install. length ($\approx 1$ cm in beam direction)

### Conventional BPM
- Easy to manufacture
- Length $= 20$ cm
- Resolution $\approx 10 \mu$m

### Rogowski BPM (warm)
- Excellent RF-signal response
- Length $= 1$ cm
- Resolution $\approx 1.25 \mu$m

- 2 coils installed at entrance and exit of RF Wien filter
Assembly stages of one Rogowski-coil BPM
High-precision beam polarimeter with internal C target

Based on LYSO scintillator readout by SiPM

- Saint-Gobain Ceramics & Plastics
- Compared to NaI:
  - high density (7.1 vs 3.67 g/cm³),
  - fast decay time (45 vs 250 ns).

After runs with external beam:

- System ready for installation at COSY (summer 2019).
- Under study: Ballistic diamond pellet target for homogeneous beam sampling.
Towards a storage ring EDM measurement
**Staged approach**

**Stage 1**
precursor experiment
at COSY (FZ Jülich)

- magnetic storage ring

now

**Stage 2**
prototype ring

- electrostatic storage ring
- simultaneous $\bigcirc$ and $\bigcirc$ beams

5 years

**Stage 3**
dedicated storage ring

- magic momentum
  (701 MeV/c)

10 years

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

- $10^{-17}$
- $10^{-18}$
- $10^{-19}$
- $10^{-20}$
- $10^{-21}$
- $10^{-22}$
- $10^{-23}$
- $10^{-24}$
- $10^{-25}$
- $10^{-26}$
- $10^{-27}$
- $10^{-28}$
- $10^{-29}$
Stage 1: proof of principle experiment using COSY

- Thomas - BMT equation for a magnetic ring:

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

storage rings: vertical B fields, radial E field

- MDM → fast spin precession in the horizontal plane
- EDM → slow vertical polarization buildup, up and down

Access to EDM through motional E field

- Pure magnetic ring → motional electric field: \( \vec{v} \times \vec{B} \)
- \( \Rightarrow \) access to EDM
Stage 1: proof of principle

RF-Wien filter

Magnetic ring
- Momentum ↑↑ spin ⇒ spin kicked up
- Momentum ↑↓ spin ⇒ spin kicked down
- ⇒ no accumulation of vert. asymmetry

RF-Wien filter
- Lorentz force: \( \vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0 \)
- \( \vec{B} = (0, B_y, 0) \) and \( \vec{E} = (E_x, 0, 0) \)
Stage 1: proof of principle

Waveguide RF-Wien filter

- Developed at FZJ in collaboration with RWTH-Aachen
- Installed in the PAX low-$\beta$ section at COSY
Stage 1: proof of principle

Waveguide RF-Wien filter

- Developed at FZJ in collaboration with RWTH-Aachen
- Installed in the PAX low-$\beta$ section at COSY
- RF-Wien filter operation:
**Stage 1: proof of principle**

**Effect of EDM on stable spin-axis**

- **EDM absence**
  - EDM absence
  - EDM effect
  - Magnetic misalignment

**EDM tilts the stable spin-axis**

- Presence of EDM $\rightarrow \varepsilon_{EDM} > 0$
  - $\rightarrow$ spin precess around the $\vec{c}$ axis
  - $\rightarrow$ oscill. vert. polarization $p_y(t)$
Stage 1: proof of principle

**Polarization buildup**

**Metod**

- Wien filter operated with B normal to the ring plane
- Measurement of initial slopes of polarization buildup:
  - $\alpha(t) = \arctan \left( \frac{P_y}{P_{xy}} \right)$
Stage 1: proof of principle

Measurement of EDM-like buildup signals

Rate out-of-plane angle $\dot{\alpha}(t)|_{t=0}$ as function of Wien filter RF phase $\phi_{RF}$

- Variation of $\phi_{rot}^{WF}$ and $\chi_{rot}^{Sol1}$ affects the pattern of observed initial slopes $\dot{\alpha}$

$\dot{\alpha}$ for $\phi_{rot}^{WF} = -1^\circ, 0^\circ, +1^\circ$ and $\chi_{rot}^{Sol1} = 0$.

$\dot{\alpha}$ for $\chi_{rot}^{Sol1} = -1, 0, +1^\circ$ and $\phi_{rot}^{WF} = 0$. 
Stage 1: proof of principle

Preliminary results from run in Dec. 18

Spin-tracking simulations necessary

- Orientation of stable spin axis at location of RF Wien filter including EDM determined by minimum of map
- Spin tracking simulation shall provide orientation of stable spin axis without EDM
- Second run foreseen in autumn 2019
Stage 1: proof of principle

Next steps
Stage 2: prototype EDM storage ring

Next step

- Build demonstrator for charged particle EDM
- Project prepared by CPEDM working group (CERN+JEDI+srEDM)
  - Physics Beyond Collider process (CERN)
  - European Strategy for Particle Physics Update
- Possible host sites: COSY or CERN

Scope of prototype ring of 100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- p at 45 MeV frozen spin including additional vertical magnetic fields

Storage time
- CW-CCW operation
- Spin-coherence time
- Polarimetry
- Magnetic moment effects
- Stochastic cooling
- pEDM measurement
Stage 2: prototype ring

Ring lattice and bending elements
Stage 3: precision EDM ring

500 m circumference ring

- All-electric deflection
- Magic momentum ($p = 701$ MeV/c)
- 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 (intentional) $B_r$ field

"Holy Grail" of storage rings (largest ever conceived)
## Conclusions

### Search for charged particle EDMs (p, d, \(^3\)He)
- EDMs → probes of CP-violating interactions
- Matter-antimatter asymmetry
- Measurements of different particles required

### Investigations at COSY
- Important achievements accomplished
- First measurement of deuteron EDM ongoing
  - Results expected end 2019

### Interest and acknowledgment
- Project acknowledged with ERC-AdG "srEDM"
- Study group established at CERN:
  - Design of a small-scale prototype ring
  - Feasibility study of a pure electrostatic EDM proton ring
Appendix
EDM of neutral particles: measurement concept

\[ h_{f+} = 2\mu B + 2dE \]
\[ h_{f-} = 2\mu B - 2dE \]
Polarized molecules: effective field

- Molecules make the highest electric field on electron

*Tl atom*

\[ E_{lab} = 123 \text{ kV/cm} \quad \rightarrow \quad E_{eff} = 72 \text{ MV/cm} \]

*ThO molecule*

\[ E_{lab} = 100 \text{ V/cm} \quad \rightarrow \quad E_{eff} = 100 \text{ GV/cm} \]
**Measurement of electron EDM**

**ThO metastable state**

Energy shifts in J=1 level of H state

\[ \Delta E_{\text{upper}} = 2g m_B B - 2d e E_{\text{eff}} \]

\[ \Delta E_{\text{lower}} = 2g m_B B + 2d e E_{\text{eff}} \]

**Omega doublet**

- Nearly degenerate (300 kHz) (opposite party)
- Change internal field direction with no lab field change
- V/cm electric field saturates
- Tiny magnetic moment (0.01 \( \mu_B \))
- \( ^3 \Delta_1 \) long lived (> 1.8 ms)
Measurement of electron EDM

Schematic of experiment
Result and impact

ACME II result (Nature 562, 355-360, 2018)

$$|d_e| < 1.1 \times 10^{-29} \text{e} \cdot \text{cm}$$

Before ACME

ACME

Measurement of electron EDM

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

- 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Julich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...)

- [http://collaborations.fz-juelich.de/ikp/jedi](http://collaborations.fz-juelich.de/ikp/jedi)
Measurement of electron EDM