Electric Dipole Moment Measurements at Storage Rings

J. Pretz
RWTH Aachen & FZ Jülich
on behalf of the JEDI collaboration

Trento, ECT*, October 2018
"Discrete symmetries in particle, nuclear and atomic physics and implications for our universe".
Outline

- Motivation for Electric Dipole Moment (EDM) Measurements
- **Charged** particle EDM measurements achievements, activities, plans
Motivation for Electric Dipole Moment (EDM) Measurements
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 $\mathcal{T}$ and parity $\mathcal{P}$ symmetry
- has nothing to do with electric dipole moments observed in some molecules (e.g. water molecule)
\[ l(J^P) = \frac{1}{2}(\frac{1}{2}^+) \]

Mass \( m = 1.00727646688 \pm 0.00000000009 \ u \)

Mass \( m = 938.272081 \pm 0.000006 \text{ MeV} \) \([a]\)

\(|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}, \text{ CL} = 90\% \) \([b]\)

\[ \left| \frac{q_\bar{p}}{m_{\bar{p}}} \right| \left( \frac{q_p}{m_p} \right) = 0.99999999991 \pm 0.00000000009 \]

\(|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}, \text{ CL} = 90\% \) \([b]\)

\(|q_p + q_e|/e < 1 \times 10^{-21} \) \([c]\)

Magnetic moment \( \mu = 2.792847351 \pm 0.000000009 \ mu_N \)

\((\mu_p + \mu_{\bar{p}})/\mu_p = (0 \pm 5) \times 10^{-6} \)

Electric dipole moment \( d < 0.54 \times 10^{-23} \text{ ecm} \)

Electric polarizability \( \alpha = (11.2 \pm 0.4) \times 10^{-4} \text{ fm}^3 \)

Magnetic polarizability \( \beta = (2.5 \pm 0.4) \times 10^{-4} \text{ fm}^3 \) \((S = 1.2)\)

Charge radius, \( \mu_p \) Lamb shift \( = 0.84087 \pm 0.00039 \text{ fm} \) \([d]\)

Charge radius, \( e_p \) CODATA value \( = 0.8751 \pm 0.0061 \text{ fm} \) \([d]\)

Magnetic radius \( = 0.78 \pm 0.04 \text{ fm} \) \([e]\)

Mean life \( \tau > 2.1 \times 10^{29} \text{ years}, \text{ CL} = 90\% \) \([f]\) \((p \rightarrow \text{ invisible mode})\)

Mean life \( \tau > 10^{31} \text{ to } 10^{33} \text{ years} \) \([f]\) \((\text{mode dependent})\)

See: "Nuclear Physics Data" (1996), vol. 2, pp. 95-147.
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both $\parallel$ to spin

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<tbody>
<tr>
<td>$H$</td>
<td>$\mathcal{T}$</td>
<td>$\mathcal{P}$</td>
</tr>
<tr>
<td>$= -\mu \hat{\vec{s}} \cdot \vec{B} - d \hat{\vec{s}} \cdot \vec{E}$</td>
<td>$= -\mu \hat{\vec{s}} \cdot \vec{B} + d \hat{\vec{s}} \cdot \vec{E}$</td>
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$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}$ ($\equiv CP$)
### CP – Violation & connection to EDMs

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<th>Standard Model</th>
<th>beyond Standard Model</th>
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<td><strong>Weak interaction</strong></td>
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**Standard Model**

- **Weak interaction**
  - CKM matrix → unobservably small EDMs

**Beyond Standard Model**

- e.g. SUSY → accessible by EDM measurements
EDM in SM and SUSY
EDM in SM and SUSY
EDM in SM and SUSY

SUSY
Excess of matter in the universe:

\[
\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}
\]

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<th>observed</th>
<th>SCM* prediction</th>
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<td>$6 \times 10^{-10}$</td>
<td>$10^{-18}$</td>
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Sakharov (1967): $CP$ violation needed for baryogenesis

$\Rightarrow$ New $CP$ violating sources beyond SM needed to explain this discrepancy

They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model
EDM: Current Upper Limits

- Electron (YbF, ThO)
- Muon
- Tau
- Neutron
- Hg

199

- Proton ($\Lambda$
- Deuteron

$10^{-19}$

$10^{-21}$

$10^{-23}$

$10^{-25}$

$10^{-27}$

$10^{-29}$

$10^{-31}$

$10^{-33}$

$10^{-35}$

$10^{-37}$

$10^{-39}$

- EDM/e \cdot cm = 0

QCD

Standard Model ($\theta_{QCD} = 0$)

CP

 SUSY ($\frac{\alpha}{\pi} < \varphi_{CP} < 1$)
EDM: Current Upper Limits

- Electron (YbF, ThO)
- Muon
- Tau
- Neutron
- Hg

- Proton ($^1$H)
- Deuteron ($^2$H)
- $^3$He

$\alpha / \pi < \varphi_{CP} < 1$

SUSY

Standard Model ($\theta_{QCD} = 0$)

Prototype ring

Dedicated storage ring

precursor exp. COSY

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

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  \[ d_d, d_p, d_n \Rightarrow \text{access to } \theta_{QCD} \]

(A. Wirzba, J. Bsaisou, A. Nogga, Int.J.Mod.Phys. E26 (2017) no.01n02, 1740031)

EDM of one particle alone not sufficient to identify \( CP \)–violating source
Sources of $CP$ Violation

- Neutron, Proton
- Nuclei: $^2H, ^3H, ^3He$
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: Tl, 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

J. de Vries
Charged particle EDM measurements achievements, activities, plans
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 polarisation $s_\perp \propto |d|$
(can be measured via elastic scattering on carbon)
Spin Precession: Thomas-BMT Equation

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

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

BMT: Bargmann, Michel, Telegdi
Spin Precession: Thomas-BMT Equation

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\]

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<thead>
<tr>
<th>1.) pure electric ring</th>
<th>no ( \vec{B} ) field needed, CW/CCW beams simultaneously works only for particles with ( G &gt; 0 ) (e.g. ( p ))</th>
</tr>
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<td>2.) combined ring</td>
<td>works for ( p, d, \textsuperscript{3}He, \ldots ) both ( \vec{E} ) and ( \vec{B} ) required</td>
</tr>
<tr>
<td>3.) pure magnetic ring</td>
<td>existing (upgraded) COSY ring can be used, shorter time scale lower sensitivity, precession due to ( G ), i.e. no frozen spin</td>
</tr>
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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
Different Options

- First measurement with existing magnetic ring COSY at FZ Jülich

**Jülich Electric Dipole Moment Investigations**

- Plans for a prototype/dedicated ring: CPEDM collaboration (CERN, JEDI, Korea, ...)

CPEDM
Experimental Requirements

- high precision storage ring → systematics (alignment, stability, field homogeneity)
- high intensity beams \( (N = 4 \cdot 10^{10} \text{ per fill}) \)
- polarized hadron beams \( (P = 0.8) \)
- long spin coherence time \( (\tau = 1000 \text{ s}) \),
- large electric fields \( (E = 10 \text{ MV/m}) \)
- polarimetry (analyzing power \( A = 0.6, \text{ acc. } f = 0.005 \))

\[
\sigma_{\text{stat}} \approx \frac{\hbar}{\sqrt{Nf\tau PAE}} \Rightarrow \sigma_{\text{stat}}(1\text{ year}) = 10^{-29} \text{ e}\cdot\text{cm}
\]

challenge: get \( \sigma_{\text{sys}} \) to the same level
COoler SYnchrotron COSY at Forschungszentrum provides (polarized) protons and deuterons with $p = 0.3 - 3.7$ GeV/c

⇒ Ideal starting point for charged hadron EDM searches
Recent achievements

1. **Spin coherence time:** $\tau > 1000$ s  
   (PRL 117, 054801 (2016))

2. **Spin tune:** $\bar{\nu}_s = -0.16097 \cdots \pm 10^{-10}$ in 100 s  
   (PRL 115, 094801 (2015))

3. **Spin feedback:** polarisation vector kept within 12 degrees  
   (PRL 119 (2017) no.1, 014801)

(all data shown were taken with deuterons, with $p \approx 1$ GeV/c)

① mandatory to reach statistical sensitivity  
② & ③ shows that we can measure and manipulate polarisation vector with high accuracy
Spin Precession

\[ \vec{P}_1 = \left\langle \sum_{i=1}^{N} \frac{\vec{S}_i}{S_i} \right\rangle \]

\[ f_{\text{spin}} = \gamma G f_{\text{rev}} \]

\[ |\vec{P}_2| < |\vec{P}_1| \]
1.) Spin Coherence Time (SCT)

deuterons p=970 MeV/c

Normalized Polarization

Time (s)

nb. turns/10^6
1.) Spin Coherence Time (SCT)

deuterons p=970 MeV/c

\[ Q = 2\pi \cdot 120\text{kHz} \cdot 1000\text{s} \approx 10^9 \]
2.) Spin Tune $\nu_S$

\[ f_{\text{spin}} = \gamma G f_{\text{rev}} \]

\[ \vec{P}_1 = \left< \sum_{i=1}^N \vec{S}_i / S_i \right> \]

\[ |\vec{P}_2| < |\vec{P}_1| \]

(a)

(b)

\[
\sigma(\nu_S = \gamma G) \approx 10^{-10} \text{ in } 100 \text{ s} \\
\sigma(\nu_S = \gamma G) \approx 10^{-8} \text{ in } 2 \text{ s}
\]
3.) Polarisation feedback

Controlling 120kHz precession
Towards a first deuteron EDM measurement

- Spin Manipulation and Measurement ✓
- In magnetic storage ring EDM just causes oscillation with tiny oscillation in vertical plane
- **Wien-filter** operating at spin precession frequency leads to vertical polarisation build-up due to EDM (and unfortunately also due to misalignments of storage ring elements)

⇒ EDM measurement possible at magnetic storage ring
Wien filter

- field: $2.7 \cdot 10^{-2}$ Tmm for 1kW input power
- frequency range: 100 kHz-2MHz
Results from Nov. 2017 Beam Time

≈ 1 day of data taking ⇒ stat. error ≈ $10^{-19}$

not a problem simulations are ongoing to understand effects of misalignments (here mimicked by rotation of WF)
Results from Nov. 2017 Beam Time

\[ d \approx 10^{-18} \text{e.cm} \]

- \( \approx 1 \) day of data taking \( \Rightarrow \) stat. error \( \approx 10^{-19} \text{ecm} \) not a problem
- Simulations are ongoing to understand effects of misalignments (here mimicked by rotation of WF)
Activities

required for first EDM measurement:
- maximize spin coherence time (SCT)
- precise measurement of spin precession (spin tune)
- polarisation feedback
- RF- Wien filter

to reduce systematic errors:
- development of high precision beam position monitors
- beam based alignment

Interpretation of results:
- spin tracking simulation (measured polarisation → EDM)
- theory (pEDM, dEDM, eEDM, ... → underlying theory)

Design of dedicated storage ring:
- accelerator lattice
- polarimeter development
- development of electrostatic deflectors

other observables:
- axion searches
  (axions may lead to oscillating EDM)
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Summary

- EDMs are unique probe to search for new CP-violating interactions
- **charged** particle EDMs can be measured in storage rings
- step wise approach: precursor at COSY $\rightarrow$ prototype ring (100 m) $\rightarrow$ dedicated ring (400 m)
Spare
Axion Search

Asymmetry Measurements

Detector signal \( N_{up, dn} \propto (1 \pm P A \sin(\gamma G \omega_{rev} t)) \)

\[
A_{up, dn} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} = PA \sin(\gamma G \omega_{rev} t)
\]

\( A \): analyzing power, \( P \): polarization

\[
A_{up, dn} = 0
\]

\[
A_{up, dn} = PA
\]
Polarimetry

Cross Section & Analyzing Power for deuterons

\[ N_{up,dn} \propto \left( 1 \pm P \cdot A \sin(\nu_s \omega_{rev} t) \right) \]

\[ A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P \cdot A \sin(\nu_s \omega_{rev} t) \]

\( A \): analyzing power
\( P \): beam polarization