Precision experiments: Search for static Electric Dipole Moments

J. Pretz
RWTH Aachen & FZ Jülich

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Motivation for Electric Dipole Moment (EDM) Measurements

Charged particle EDM measurements
  Principle & recent progress

Activities around the world
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 do due with electric dipole moments observed in some molecules (e.g. water molecule)
\[ l(J^P) = \frac{1}{2}(1/2^+) \]

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

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

\[ \frac{m_p - m_{\bar{p}}}{m_p} < 7 \times 10^{-10}, \text{ CL = 90\%} \]

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

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

\[ \frac{|q_p| + q_e}{e} < 1 \times 10^{-21} \]

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 \( d < 0.54 \times 10^{-23} \) ecm

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

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

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

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

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

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

Mean life \( \tau > 10^{31} \) to \( 10^{33} \) years \( [f] \) \( \) (mode dependent)
\[ \vec{d}: \text{EDM} \]
\[ \vec{\mu}: \text{magnetic moment} \]
both \( \parallel \) to spin

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

\( \Rightarrow \) EDM measurement tests violation of fundamental symmetries \( \mathcal{P} \) and \( \mathcal{T}(\overset{\text{CP}}{\cong}) \)
**$CP$—Violation & connection to EDMs**

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

\[ \gamma \to d \bar{d}^0 \chi \]
CP violation & Matter-Antimatter Asymmetry

Excess of matter in the universe:

\[
\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \quad \text{observed} \quad 6 \times 10^{-10} \quad \text{SCM* prediction} \quad 10^{-18}
\]

Sakharov (1967): \(C\bar{P}\) violation needed for baryogenesis

⇒ New \(C\bar{P}\) 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
- Proton
- \( \Lambda \)
- Deuteron

\[ \text{edm/e} \cdot \text{cm} \]

- \(10^{-15}\)
- \(10^{-17}\)
- \(10^{-19}\)
- \(10^{-21}\)
- \(10^{-23}\)
- \(10^{-25}\)
- \(10^{-27}\)
- \(10^{-29}\)
- \(10^{-31}\)
- \(10^{-33}\)
- \(10^{-35}\)
- \(10^{-37}\)
- \(10^{-39}\)

- SUSY \(\frac{\alpha}{\pi} < \varphi_{\text{CP}} < 1\)
- Standard Model \(\theta_{\text{QCD}} = 0\)
EDM: Current Upper Limits

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:
  \[ d_d, d_p, d_n \Rightarrow \text{access to } \theta_{QCD} \]

EDM of one particle alone not sufficient to identify $C\bar{P}$–violating source
Sources of $CP$ Violation

- Neutron, Proton
- Nuclei: $^2\text{H}, ^3\text{H}, ^3\text{He}$
- 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
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/magnetic 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 $s_\perp \propto |d|$
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 \( A = 0.6 \), acc. \( f = 0.005 \))

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

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

$\Rightarrow$ **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
   (acc. for publication in PRL)

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

\[ \vec{P}_1 = \frac{1}{N} \sum_{i=1}^{N} \vec{S}_i / S_i \]

\[ \vec{f}_{spin} = \gamma G \vec{f}_{rev} \]

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

deuterons $p=970$ MeV/$c$

Normalized Polarization

$\Delta$

Time (s)
1.) Spin Coherence Time (SCT)

Deuterons $p = 970 \text{ MeV}/c$

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

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

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

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

$\sigma(\nu_S = \gamma G) \approx 10^{-10}$ in 100 s

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

Controlling 120kHz precession
Charged hadron EDM activities

**srEDM**
- Since ≈2000, BNL/Korea
- Design for $E$ ring for proton

**JEDI**
- Since 2011, Jülich/Aachen
- EDM experiments at COSY, design for $E/B$ ring

**CPEDM**
- Since 2017, CERN
- Feasibility study for EDM ring at CERN
  (Physics beyond collider workshop)
Storage ring steps up search for electric dipole moments

The JEDI collaboration aims to use a storage ring to set the most stringent limits to date on the electric dipole moments of hadrons, describe Paolo Lenisa, Jörg Pretz and Hans Ströher.
EDMs are unique probe to search for new CP-violating interactions

**charged** particle EDM searches require new high precision storage rings

cooperation with CERN started: feasibility study end 2018