Electric Dipole Moment Measurements at Storage Rings

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for the JEDI collaboration

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Outline

- Introduction & Motivation
  What are EDMs?, What do we know about EDMs?
  Why are EDMs interesting?

- Experimental Methods
  How to measure charged particle EDMs?

- Recent Achievements
  How do manipulate and measure a polarization with high precision!
Electric Dipole Moments (EDM)

- 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
Mass $m = 1.00727646681 \pm 0.0000000009 \ u$

Mass $m = 938.272046 \pm 0.000021 \ MeV \ [a]$

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

$|\frac{q_\pi}{m_p}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.0000000009$

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

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

Magnetic moment $\mu = 2.792847356 \pm 0.000000023 \ \mu_N$

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

**Electric dipole moment** $d < 0.54 \times 10^{-23} \ \text{e cm}$

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 = $0.8775 \pm 0.0051 \ \text{fm} \ [d]$

Magnetic radius = $0.777 \pm 0.016 \ \text{fm}$

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

Mean life $\tau > 10^{31} \text{ to } 10^{33} \text{ years} \ [e] \ \ (\text{mode dependent})$
\( \mathcal{T} \) and \( \mathcal{P} \) violation of EDM

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

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

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

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

\( \Rightarrow \) EDM measurement tests violation of fundamental symmetries \( \mathcal{P} \) and \( \mathcal{T}(\mathcal{CP} \equiv \mathcal{T}) \)
### $\mathcal{CP}$ – Violation and connection to EDMs

<table>
<thead>
<tr>
<th>Standard Model</th>
<th>Weak interaction</th>
<th>Strong interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CKM matrix</td>
<td>→ unobservably small EDMs</td>
<td>$\theta_{QCD}$ → best limit from neutron EDM</td>
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<td>e.g. SUSY</td>
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**Weak interaction**
- CKM matrix: $\mathcal{CP}$ violation leads to unobservably small EDMs.

**Strong interaction**
- $\theta_{QCD}$: Best limit from neutron EDM.

**Beyond Standard Model**
- e.g. SUSY: Accessible by EDM measurements.
Matter-Antimatter Asymmetry

Excess of matter in the universe:

<table>
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<th></th>
<th>observed</th>
<th>SCM* prediction</th>
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<td>$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$</td>
<td>$6 \times 10^{-10}$</td>
<td>$10^{-18}$</td>
</tr>
</tbody>
</table>

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
What do we know about EDMs?
EDM: Current Upper Limits

- Muon
- Tau
- Neutron
- Hg
- Proton
- Deuterium

$10^{-17}$ to $10^{-39}$

**SUSY** ($\frac{\alpha}{\pi} < \varphi_{CP} < 1$)

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

**FZ Jülich: EDMs of charged hadrons: $p, d, ^3He$**
EDM: Current Upper Limits

Goal exp. at COSY ($10^{-24}$ e cm)
Goal dedicated ring ($10^{-29}$ e cm)

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 $CP$–violating source
How to measure charged particle EDMs?
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 $s_\perp \propto |d|$
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 \( A = 0.6, \text{ acc. } f = 0.005 \))

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

**Challenge**: get \( \sigma_{\text{sys}} \) to the same level
Spin Precession: Thomas-BMT Equation

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

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

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

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

1.) pure electric ring
   - no \(\vec{B}\) field needed,
   - works only for particles with \(G > 0\) (e.g. \(p\))

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

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

2.) combined ring

- works for \( p, d, ^3\text{He}, \ldots \)
- both \( \vec{E} \) and \( \vec{B} \) required

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

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

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

BMT: Bargmann, Michel, Telegdi
Recent Achievements:
How do manipulate and measure a polarization with high precision!
COSY provides (polarized) protons and deuterons with
\[ p = 0.3 - 3.7 \text{GeV}/c \]
⇒ **Ideal starting point for charged particle EDM searches**
Polarized proton & deuterons

Polarimeter

RF $E \times B$ dipole

RF solenoid

sextupoles

cooled beams: e-cooling, stochastic cooling
R & D at COSY

- maximize spin coherence time (SCT) (→ E. Stephenson, Tue. 15.20)
- precise measurement of spin precession (spin tune)
- polarization feedback (→ N. Hempelmann, Tue. 14.45)
- spin tracking simulation tools, design of dedicated storage ring (→ M. Rosenthal, Tue. 14.30, E. Valetov, Tue. 11.30)
- RF-Wien filter design and construction (→ J. Slim, Tue. 14.55)
- tests of electro static deflectors (goal: field strength > 10 MV/m)
- development of high precision beam position monitors
- polarimeter development

More related talks on this conference: R. Talman (Tue. 11.55), B. Lorentz (Mon. 14.55), Y. Duteil (Mon. 14.30), W. Hillert (Tue. 12.20)
Inject and accelerate vertically polarized deuterons to $p \approx 1 \text{ GeV}/c$
Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1 \text{ GeV/c}$
- Flip polarization with help of solenoid into horizontal plane, precession starts
Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1 \text{ GeV}/c$
- Flip polarization with help of solenoid into horizontal plane, precession starts
- Extract beam slowly (in $\approx 100 \text{ s}$) on target
- Measure asymmetry and determine spin precession
Polarimeter

elastic deuteron-carbon scattering, consists of four scintillator segments: left, right, up, down

asymmetry $A_{up,down} \propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$
asymmetry $A_{left,right} \propto$ vertical polarization $\rightarrow d$
Asymmetries

\[ \vec{B} \]

\[ \vec{B} \]

\[ 120 \text{ kHz} \]

\[ \tau = 8.3 \mu \text{s} \]

\[ A_{\text{left,right}} \]

\[ A_{\text{up,dn}} \]

\[ t = 10 - 1000 \text{s} \]
Polarization Flip

- Left-Right-Asymmetry $\propto P_y$
- Up-Down-Asymmetry $\propto P_x$

$\vec{B}$ envelope with initial polarization up (down)

$(\uparrow \downarrow)$ cycle with initial polarization up (down)
Polarization Flip

\[ \vec{B} \]

\[ \vec{B} \]

envelope of cycle with initial polarization up (down)

\[ P \propto \text{Left-Right-Asymmetry} \]

\[ P \propto \text{Up-Down-Asymmetry} \]
Polarization Flip

(.cycle with initial polarization up (down)

⃗B

envelope of cycle with initial polarization up (down)
Results: Spin Coherence Time (SCT)

**Short Spin Coherence Time**

Horizontal Asymmetry Run: 2042

\[ \chi^2 / \text{ndf} = 69.29 / 90 \]
\[ \text{Amplitude} = 0.282 \pm 0.006 \]
\[ \frac{1}{\text{SCT}} = -0.04968 \pm 0.00145 \]

unbunched beam
\[ \Delta p / p = 10^{-5} \Rightarrow \Delta \gamma / \gamma = 2 \cdot 10^{-6}, \ T_{rev} \approx 10^{-6} \text{ s} \]
\[ \Rightarrow \text{decoherence after } < 1 \text{ s} \]
bunched beam eliminates 1st order effects in \( \Delta p / p \)
\[ \Rightarrow \text{SCT } \tau = 20 \text{ s} \]
Results: Spin Coherence Time (SCT)

**Long Spin Coherence Time**

SCT of $\tau = 400$ s, after correction with sextupoles (chromaticities $\xi \approx 0$)
SCT: Longer Cycles

PRL 117 (2016) no.5, 054801.
SCT: Longer Cycles

\[ Q = 2\pi \cdot 120\text{KHz} \cdot 1000\text{s} \approx 10^9 \]
Spin Tune $\nu_s$

Spin tune: $\nu_s = \gamma G = \frac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$

deuterons: $p_d = 1 \text{ GeV/c} \ (\gamma = 1.13), \ G = -0.14256177(72)$

$\Rightarrow \nu_s = \gamma G \approx -0.161$
Results spin tune

$\sin(\nu_s(t)\omega_{rev} t + \varphi) = \sin(\nu_s^0\omega_{rev} t + \varphi(t))$
Results spin tune

\[\sin(\nu_s(t)\omega_{\text{rev}} t + \varphi) = \sin(\nu_s^0\omega_{\text{rev}} t + \varphi(t))\]

\[\sigma_{\nu_s} \approx 10^{-8}\]
Results spin tune

\[ \sin(\nu_s(t)\omega_{\text{rev}} t + \varphi) = \sin(\nu_0^s\omega_{\text{rev}} t + \varphi(t)) \]

\[ \sigma_{\nu_s} \approx 10^{-8} \]

\[ \sigma_{\nu_s} \approx 10^{-10} \]
Spin Tune Measurement

\[ \vec{P} = \langle \vec{s}_i \rangle \]

\[ f_s = \nu_s f_{\text{rev}} \]

- precision $10^{-10}$ in one cycle of $\approx 100$ s
  (translated to angle, precision is $2 \cdot \pi \cdot 10^{-10} = 0.6$ nrad)
- spin tune measurement can now be used as tool to investigate systematic errors
- spin tune measurement allows for feedback system to keep polarization aligned with momentum vector for dedicated ring or at a given phase with respect to radio-frequency Wien filter
Spin Feed back system

- polarization rotation in horizontal plane at $t = 85\ s$
- COSY rf changed during cycle in steps of 3.7 mHz ($f_{\text{rev}}=750603\ \text{Hz}$) according to online $\nu_s$ measurement,
- keeps phase between spin and RF solenoid constant
- solenoid (low amplitude) switched on at $t = 115\ s$
- polarization goes back to vertical direction
- mandatory for \textit{frozen spin} in dedicated ring
Simulations

- EDM signal is build-up of vertical polarization
- radial magnetic fields ($B_r$) cause the same build-up
- misalignments of quadrupoles create for example unwanted $B_r$
- ⇒ Run simulations to understand systematic effects
- General problem: Track $10^9$ particles for $10^9$ turns!  
  (⇒ use transfer maps of magnet elements (code: COSY Infinity))
- orbit RMS $\Delta y_{RMS}$ is measure of misalignments
Random Misalignments from $1\mu$m to 1 mm, Use of CW/CCW beams requires only relative measurement of two beams
JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 100 members
  (Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...)
- ≈ 10 PhD students
- close collaboration with srEDM collaboration in US/Korea

http://collaborations.fz-juelich.de/ikp/jedi/index.shtml
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.

The fact that we and the world around us are made of matter and only

Search for electric dipole moments using storage rings
PI: H. Ströher, (FZ Jülich), RWTH Aachen University, University of Ferrara
Start: Oct, 1st, 2016
EDMs of elementary particles are of high interest to disentangle various sources of \textit{CP violation} searched for to explain \textit{matter - antimatter asymmetry} in the Universe.

EDM of \textit{charged} particles can be measured in \textit{storage rings}.

Experimentally very challenging because effect is tiny.

First promising results:

- \textit{spin coherence time}: \(\approx 1000 \text{ s}\)
- \textit{spin tune}: \(10^{-10}\) in 100 s
- \textit{feed back system} allows to control spin
- \textit{simulations} to understand systematics