Electric Dipole Moment (EDM) Searches in Storage Rings

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RWTH Aachen/ FZ Jülich

Outline

- Introduction & Motivation
- Measurement of charged particle EDMs
- Jülich efforts to measure EDMs
  (Jülich Electric Dipole Moment Investigations (JEDI) collaboration)
- Summary
Introduction & Motivation
Electric Dipoles

Classical definition:

\[ \vec{d} = \sum_i q_i \vec{r}_i \]
Order of magnitude

**atomic physics:**

\[ q_1 = -q_2 = e, \quad |\vec{r}_1 - \vec{r}_2| = 1\text{Å} = 10^{-10}\text{m} \]

\[ \rightarrow |\vec{d}| = 10^{-8}e\cdot\text{cm} \]

Water molecule: \(d = 2 \cdot 10^{-9}e\cdot\text{cm}\)
Order of magnitude

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Water molecule: \( d = 2 \cdot 10^{-9}e \cdot \text{cm} \)

**hadron physics:**

\[ |\vec{r}_1 - \vec{r}_2| = 1\text{fm} = 10^{-13}\text{cm} \]

\[ \rightarrow |\vec{d}| = 10^{-13}e \cdot \text{cm} \]

Limit on neutron EDM < 3 \cdot 10^{-26}e\cdot\text{cm}
Operator $\vec{d} = q\vec{r}$

is odd under parity transformation ($\vec{r} \rightarrow -\vec{r}$):

$$P^{-1}\vec{d}P = -\vec{d}$$

Consequences:
In a state $|a\rangle$ of given parity the expectation value is 0:

$$\langle a|\vec{d}|a\rangle = -\langle a|\vec{d}|a\rangle$$

If $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$

in general $\langle a|\vec{d}|a\rangle \neq 0$
Order of magnitude

Molecules can have large EDM because of degenerate ground states with different parity
Order of magnitude

**Molecules** can have large EDM because of degenerate ground states with different parity.

\[
\psi_s = \frac{1}{\sqrt{2}} (\psi_1 + \psi_2) \quad P = +
\]

\[
\psi_a = \frac{1}{\sqrt{2}} (\psi_1 - \psi_2) \quad P = -
\]

(Allmost) degenerated states with different parity:

\[
|a\rangle = \alpha |\psi_s\rangle + \beta |\psi_a\rangle
\]

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)
Order of magnitude

**Molecules** can have large EDM because of degenerate ground states with different parity

**Elementary particles** (including hadrons) have a definite parity and cannot possess an EDM

\[ P|\text{had} \rangle = \pm 1|\text{had} \rangle \]
Order of magnitude

**Molecules** can have large EDM because of degenerate ground states with different parity

**Elementary particles** (including hadrons) have a definite parity and cannot possess an EDM

$P|\text{had}\rangle = \pm 1|\text{had}\rangle$

unless

$P$ and time reversal $T$ invariance are violated!
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$: EDM

$\vec{\mu}$: magnetic moment

both $\parallel$ to spin

$$H = -\mu \vec{\sigma} \cdot \vec{B} - d \vec{\sigma} \cdot \vec{E}$$

$\mathcal{T}$: $H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$

$\mathcal{P}$: $H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$

$\mathcal{T}$ violation $\xrightarrow{\mathcal{CPT}}$ $\mathcal{CP}$ violation
\( \text{CP violation} \)

- We are surrounded by matter (and not anti–matter)
  \[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 10^{-10} \]
- Starting from equal amount of matter and anti-matter at the Big Bang, from \( \text{CP} \)-violation in Standard Model we expected only \( 10^{-18} \)
- In 1967 Sakharov formulated three prerequisites for baryogenesis. One of these is the combined violation of the charge and parity, \( \text{CP} \), symmetry.
- New \( \text{CP} \) violating sources outside the realm of the SM are clearly needed to explain this discrepancy of eight orders of magnitude.
- They could manifest in EDMs of elementary particles
Sources of $\mathcal{CP}$ violation

- Weak Interaction (unobservably small in EDMs)
- QCD $\theta$ term (limit set by neutron EDM measurement)
  ——— Part of Standard Model ———
- sources beyond SM
Sources of $CP$ violation

- Leptons
- Nucleons
- Nuclei
- Atoms
- Molecules
- Atomic theory
- Nuclear interaction
- QCD
- Sources of $CP$ (CKM, BSM)
Sources of $CP$ violation

⇒ It is mandatory to measure EDM of many different particles to disentangle various sources of $CP$ violation.
What do we know about (hadron) EDMs?

<table>
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<tr>
<th>Particle/Atom</th>
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<td>$&lt; 3 \cdot 10^{-26}$</td>
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<td>$^{199}$Hg $\rightarrow$ Proton</td>
<td>$&lt; 3.1 \cdot 10^{-29}$</td>
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<td>Deuteron</td>
<td>?</td>
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<td>$^3$He</td>
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- direct measurement only for neutron
- proton deduced from atomic EDM limit
- no measurement for deuteron (or other nuclei)
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**GOAL of JEDI collaboration:**
First measurement of deuteron, $^{3}$He EDM, first direct measurement of proton EDM ultimately with a precision of $10^{-29}$ e·cm
History of Neutron EDM

50 years of effort

Extensions of SM allow for large EDMs

Electro-weak standard model expectation: $\sim 10^{-32}$ e-cm

from K. Kirch
History of Neutron EDM

50 years of effort

Extensions of SM allow for large EDMs

charged particle EDMs:

two (parasitic) measurements:

\[ d_\mu < 1.9 \cdot 10^{-19} \text{ e\cdot cm} \]

G. W. Bennett PRD 80 (2009) 052008

\[ d_\lambda = -3.0 \pm 7.4 \cdot 10^{-16} \text{ e\cdot cm} \]

L. Pondron et al. PRD, Vol. 23 (1981) 814

Electro-weak standard model expectation: \(\sim 10^{-32} \text{ e\cdot cm} \)

from K. Kirch

10^{-26}
10^{-24}
10^{-22}
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

1E-19
1E-21
1E-23
1E-25
1E-27
1E-29

1950
1960
1970
1980
1990
2000

Experiment

Theory [e cm]

Electromagnetic

Weinberg multi-Higgs

SUSY

Left-Right Symmetric

from K. Kirch
Measurement of charged particle EDMs
Measurement of charged particle EDMs

General Idea:

For all edm experiments (neutron, proton, atom, ...):

Interaction of \( \vec{d} \) with electric field \( \vec{E} \)

For charged particles: apply electric field in a storage ring:

\[
\frac{d\vec{s}}{dt} \propto \vec{E} \times \vec{d}
\]

Wait for build-up of vertical polarization \( s_\perp \propto |d| \), then determine \( s_\perp \) using polarimeter

In general: \( \frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} \)
“Thomas-BMT” formula

\[ \tilde{\Omega} = \frac{e\hbar}{mc} [G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{1}{2} \eta (\vec{E} + \vec{v} \times \vec{B})] \]

\[ \vec{d} = \eta \frac{e\hbar}{2mc} \vec{S}, \quad \vec{\mu} = 2(G + 1) \frac{e\hbar}{2m} \vec{S}, \quad G = \frac{g - 2}{2}, \quad g: g\text{-factor} \]

Several Options:

1. Pure electric ring with \((G - 1)(\gamma^2 - 1) = 0\), works only for \(G > 0\)
2. Combined \(\vec{E}/\vec{B}\) ring \(G\vec{B} + (G - 1)\gamma^2 = 0\)
3. Pure magnetic ring
“Thomas-BMT” formula

\[ \tilde{\Omega} = \frac{e\hbar}{mc} [G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) \vec{v} \times \vec{E} + \frac{1}{2} \eta (\vec{E} + \vec{v} \times \vec{B})] \]

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   \( G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) \vec{v} \times \vec{E} = 0 \)
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2. **Combined \( \vec{E}/\vec{B} \) ring**
   
   \[ G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} = 0 \]

3. **Pure magnetic ring**
### Required field strength

\[
G = \frac{g-2}{2} \quad p/\text{GeV}/c \quad E_R/\text{MV}/\text{m} \quad B_V/\text{T}
\]

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<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>1.79</td>
<td>0.701</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>deuteron</td>
<td>−0.14</td>
<td>1.0</td>
<td>−4</td>
<td>0.16</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>−4.18</td>
<td>1.285</td>
<td>17</td>
<td>−0.05</td>
</tr>
</tbody>
</table>

Ring radius \(\approx 40\text{m}\)

Smaller ring size possible if \(B_V \neq 0\) for proton

\[
E = \frac{GBc\beta\gamma^2}{1 + G\beta^2\gamma^2}
\]
1. Pure Electric Ring

Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions of the all-in-one lattice of Fig. 1 will be quite close to those given for this lattice in reference[3]. The match will be even closer with magnetic field set to zero for proton operation.

Brookhaven National Laboratory (BNL) Proposal
2. Combined $\vec{E}/\vec{B}$ ring

magnetic field (down)  polarimetry+ RF straight  utility straight
magnetic steering
magnetic field (up)  electric defocus (horz)  electric bend field
electric focus (horz)
electric bend field
vertical tune modulating electric quad  magnetometers  injection straight

Figure 1: “All-In-One” lattice for measuring EDM’s of protons, deuterons, and helions.

Under discussion in Jülich (design: R. Talman)
3. Pure Magnetic Ring

Main advantage:
Experiment can be performed at the existing (upgraded) COSY (COoler SYnchrotron) in Jülich on a shorter time scale!

COSY provides (polarized) protons and deuterons with $p = 0.3 - 3.7\text{GeV}/c$ ⇒ Ideal starting point
3. Pure Magnetic Ring

\[ \Omega = \frac{e \hbar}{mc} \left( G\vec{B} + \frac{1}{2} \eta \vec{v} \times \vec{B} \right) \]

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is \( \parallel \) to momentum, 50% of the time it is anti-\( \parallel \).

\[ \vec{E}^* = \vec{v} \times \vec{B} \]

\[ \vec{s} \rightarrow \vec{p} \]

\[ 50\% \ \vec{s}_d = \bigotimes \]

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\[ \vec{E}^* \]
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\[ \vec{E}^* = \vec{v} \times \vec{B} \]

\[ 50\% \quad \dot{s}_d = \bigotimes \]

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\[ E^* \text{ field in the particle rest frame tilts spin due to EDM up and down} \]

\[ \Rightarrow \text{no net EDM effect} \]
3. Pure Magnetic Ring

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Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is \( \parallel \) to momentum, 50% of the time it is anti-\( \parallel \).

\[ \vec{E}^* = \vec{v} \times \vec{B} \]

\( \vec{s} \rightarrow \vec{p} \)

\( > 50\% \ \dot{\vec{s}}_d = \bigotimes \)

\( < 50\% \ \dot{\vec{s}}_d = \bigotimes \)

\( E^* \) field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect

Use resonant “magic Wien-Filter” in ring (\( \vec{E} + \vec{v} \times \vec{B} = 0 \)):
\( E^* = 0 \rightarrow \) part. trajectory is not affected but \( B^* \neq 0 \rightarrow \) mag. mom. is influenced

\( \Rightarrow \) net EDM effect can be observed!
## Summary of different options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.) pure electric ring (BNL)</td>
<td>no ( \vec{B} ) field needed</td>
<td>works only for ( p )</td>
<td></td>
</tr>
<tr>
<td>2.) combined ring (Jülich)</td>
<td>works for ( p, d, ^3\text{He}, \ldots )</td>
<td>both ( \vec{E} ) and ( \vec{B} ) required</td>
<td></td>
</tr>
<tr>
<td>3.) pure magnetic ring (Jülich)</td>
<td>existing (upgraded) COSY ring can be used, shorter time scale</td>
<td>lower sensitivity</td>
<td></td>
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Statistical Sensitivity

\[ \sigma \approx \frac{\hbar}{\sqrt{NfT \tau_p \text{PEA}}} \]

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<tr>
<td>P</td>
<td>beam polarization</td>
<td>0.8</td>
</tr>
<tr>
<td>( \tau_p )</td>
<td>Spin coherence time/s</td>
<td>1000</td>
</tr>
<tr>
<td>E</td>
<td>Electric field/MV/m</td>
<td>10</td>
</tr>
<tr>
<td>A</td>
<td>Analyzing Power</td>
<td>0.6</td>
</tr>
<tr>
<td>N</td>
<td>nb. of stored particles/cycle</td>
<td>(4 \times 10^7)</td>
</tr>
<tr>
<td>f</td>
<td>detection efficiency</td>
<td>0.005</td>
</tr>
<tr>
<td>T</td>
<td>running time per year/s</td>
<td>(10^7)</td>
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\( \Rightarrow \sigma \approx 10^{-29} \text{e}\cdot\text{cm/year} \) (for magnetic ring \(\approx 10^{-24} \text{e}\cdot\text{cm/year}\))

Expected signal \(\approx 3\text{nrad/s} \) (for \(d = 10^{-29} \text{e}\cdot\text{cm}\))

(BNL proposal)
Systematics

One major source:
Radial $B$ field mimics an EDM effect:

- Difficulty: even small radial magnetic field, $B_r$ can mimic EDM effect if: $\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} \text{e}\cdot\text{cm}$ in a field of $E = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu N} = \frac{10^{-22} \text{eV}}{3.1 \cdot 10^{-8} \text{eV/T}} \approx 3 \cdot 10^{-17} \text{T}$$
  (Earth Magnetic field $\approx 5 \cdot 10^{-5} \text{T}$)

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to $B_r$
Main Challenges

- Spin Coherence Time (SCT) ≈ 1000s
- Polarimetry on 1 ppm level (ppm = part per million)
- Beam positioning ≈ 10nm (relative between CW-CCW)
- Field Gradients ≈ 10MV/m
Spin Coherence Time (SCT)

Usually we don't care about decoherence of spins because polarisation with respect to invariant spin axis $\vec{n}$ is the same.

Situation is different if $\vec{S} \perp \vec{n}$.

Longitudinal Polarization is lost.
Results on Spin Coherence Time (SCT)

Spins decohere during storage time
very preliminary results form Cosy run May 2012 using
correction sextupole

⇒ SCT increase from a few s to ≈ 200s already reached

(Ed. Stephenson)
Polarimeter

Principle: Particles hit a target:
Left/Right asymmetry gives information on EDM
Up/Down asymmetry gives information on g-2
Polarimeter

Cross Section & Analyzing Power for deuterons


FOM = σA²

Available at COSY desired range
Polarimeter

Available at COSY for tests:
EDDA polarimeter
Jülich efforts to measure EDMs
Stepwise approach of JEDI project in Jülich

JEDI = Jülich Electric Dipole Moment Investigations

1. Spin coherence time studies
   Systematic Error studies

2. COSY upgrade
   first direct measurement
   at $10^{-24} \text{e} \cdot \text{cm}$

3. Build dedicated ring for $p, d$ and $^3\text{He}$

4. EDM measurement
   at $10^{-29} \text{e} \cdot \text{cm}$
Storage Ring EDM Efforts

Common R&D work
- Spin Coherence Time
- BPMs
- Spin Tracking
- Polarimetry
- ...

BNL
- all electric ring (p)

Jülich
- first direct measurement with upgraded COSY
- all-in-one ring (p,d,${}^3$He)
JARA FAME

JARA=Jülich Aachen Research Alliance
New section founded: FAME (=Forces and Matter Experiments)

Is there anti-matter in the Universe?

- yes
  - AMS will discover it!

- no
  - JEDI will discover it!
EDM of various hadrons species are of high interest to disentangle various sources of $CP$ violation searched for to explain matter - antimatter asymmetry in the Universe.

Up to now only direct measurement for neutron.

EDM of charged particles can be measured in storage rings.

Experimentally very challenging because effect is tiny.

Efforts at Brookhaven and Jülich to perform such measurements.