Measurement of Electric Dipole Moments of Charged Particles in Storage Rings

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on behalf of the JEDI collaboration

NUPECC workshop, Jülich, March 2013
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:**

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

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

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 ($\vec{r} \rightarrow -\vec{r}$):

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

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 degenerated ground states with different parity.
Order of magnitude

**Molecules** can have large EDM because of degenerated 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 degenerated 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

\[ \mathcal{P} \text{ and time reversal } \mathcal{T} \text{ invariance are violated!} \]
$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both $\parallel$ to spin

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

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

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

$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T} (\equiv C\mathcal{P})$
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 $CP$-violation in Standard Model we expect only $10^{-18}$

In 1967 Sakharov formulated three prerequisites for baryogenesis. One of these is the combined violation of the charge and parity, $CP$, symmetry.

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

<table>
<thead>
<tr>
<th>Particle</th>
<th>EDM Value (10^-39 cm)</th>
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<tbody>
<tr>
<td>Electron (YbF)</td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td></td>
</tr>
<tr>
<td>Neutron</td>
<td></td>
</tr>
<tr>
<td>Deuteron (199Hg)</td>
<td></td>
</tr>
<tr>
<td>Proton (YbF)</td>
<td></td>
</tr>
</tbody>
</table>

- Standard Model
- SUSY
What do we know about EDMs?

- no EDM observed yet, only limits
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- no measurement for deuteron (or heavier nuclei),
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- no EDM observed yet, only limits
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- Standard Model value essentially 0
- Beyond SM values accessible by experiments
What do we know about EDMs?

GOAL of JEDI collaboration:
First measurement of deuteron, $^3$He EDM, first direct measurement of proton EDM ultimately with a precision of $10^{-29} \text{ e cm}$
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
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:

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

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

In general: \[
\frac{d\vec{s}}{dt} = \tilde{\Omega} \times \vec{s}
\]
“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 (try to get rid terms \( \propto G \)):
“Thomas-BMT” formula

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

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Several Options (try to get rid terms \( \propto G \)):

- **Pure electric ring**
  
  with \( G - \frac{1}{\gamma^2 - 1} = 0 \), works only for \( G > 0 \)
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1. **Pure electric ring**
   
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2. **Combined \( \vec{E}/\vec{B} \) ring**

   \[ G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} = 0 \]
“Thomas-BMT” formula

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

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   \( G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} = 0 \)

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

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

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<thead>
<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

\[
E = \frac{GBc\beta\gamma^2}{1 + G\beta^2\gamma^2}
\]
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.
2. Combined $\vec{E}/\vec{B}$ ring

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 \Rightarrow $ Ideal starting point
3. Pure Magnetic Ring

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

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

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

\( \vec{s} \) field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect

[Diagram with arrows showing the directions of \( \vec{s}, \vec{p}, \vec{E}^*, \vec{B} \), and \( \vec{s}_d \).]

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

\( 50\% \ \vec{s}_d = \bigcirc \)
3. Pure Magnetic Ring

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

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

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

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

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

\[ \sigma \approx \frac{\hbar}{\sqrt{N f T \tau_p PEA}} \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<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>
</tr>
</tbody>
</table>

\[ \Rightarrow \sigma \approx 10^{-29} \text{e}\cdot\text{cm/year} \text{ (for magnetic ring \(\approx 10^{-24} \text{e}\cdot\text{cm/year}\))} \]

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

(BNL proposal)
Results on Spin Coherence Time (SCT)

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

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

(Ed. Stephenson)
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 $E = 10\text{MV}/\text{m}$
- This corresponds to a magnetic field:
  \[ B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} \text{eV}}{3.1 \cdot 10^{-8} \text{eV}/\text{T}} \approx 3 \cdot 10^{-17} \text{T} \]
  (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 $B_r$
Jülich efforts to measure EDMs
JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 80 members
  (Aachen, Dubna, Ferrara, Ithaca, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, ...)
- ≈ 10 PhD students
**Stepwise approach of JEDI project in Jülich**

JEDI = Jülich Electric Dipole Moment Investigations

<p>| | |</p>
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</table>
| 1 | Spin coherence time studies  
    | Systematic Error studies |
| 2 | COSY upgrade  
    | first (direct) measurement of $p$ and $d$  
    | at $10^{-24}$ e· cm |
| 3 | Build dedicated ring for  
    | $p, d$ and $^3$He |
| 4 | EDM measurement  
    | at $10^{-29}$ e· cm |
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,³He)
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!
Summary

- EDM of charged particles can be measured in storage rings
- 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
- Experimentally very challenging because effect is tiny
- Efforts at Brookhaven and Jülich to perform such measurements
Spare
EDM of molecules

ground state: mixture of

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

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

(allmost) degenerated states with different parity:

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

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)
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.
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
Polarimeter

Available at COSY for tests:
EDDA polarimeter