Electric Dipole Moments – probes of fundamental symmetries

J. Pretz
RWTH Aachen/ FZ Jülich

Aachen, Juni 2013
Electric Dipole Moments (EDMs)

- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure (charged particle) EDMs?
What is it?
Electric Dipoles

Classical definition:

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

<table>
<thead>
<tr>
<th></th>
<th>atomic physics</th>
<th>hadron physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>charges</td>
<td>$e$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\vec{r}_1 - \vec{r}_2</td>
<td>$</td>
</tr>
<tr>
<td>EDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>naive expectation</td>
<td>$10^{-8}e \cdot \text{cm}$</td>
<td></td>
</tr>
<tr>
<td>observed</td>
<td>water molecule</td>
<td>$2 \cdot 10^{-8}e \cdot \text{cm}$</td>
</tr>
</tbody>
</table>
## Order of magnitude

<table>
<thead>
<tr>
<th></th>
<th>atomic physics</th>
<th>hadron physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>charges</td>
<td>$e$</td>
<td>$e$</td>
</tr>
<tr>
<td>$</td>
<td>\vec{r}_1 - \vec{r}_2</td>
<td>,$</td>
</tr>
<tr>
<td>EDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>naive expectation</td>
<td>$10^{-8} e \cdot \text{ cm}$</td>
<td>$10^{-13} e \cdot \text{ cm}$</td>
</tr>
<tr>
<td>observed</td>
<td>water molecule</td>
<td>neutron</td>
</tr>
<tr>
<td></td>
<td>$2 \cdot 10^{-8} e \cdot \text{ cm}$</td>
<td>$&lt; 3 \cdot 10^{-26} e \cdot \text{ cm}$</td>
</tr>
</tbody>
</table>
neutron EDM of $d_n = 3 \cdot 10^{-26} \text{e}\cdot\text{cm}$ corresponds to separation of $u$– from $d$–quarks of $\approx 5 \cdot 10^{-26} \text{cm}$
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 $\langle a|\vec{d}|a\rangle \neq 0 \Rightarrow$ i.e. molecules
EDM of molecules

ground state: mixture of

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

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

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)
**Molecules** can have large EDM because of degenerated ground states with different parity.
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.

\[ P | \text{had} > = \pm 1 | \text{had} > \]

unless

\[ P \text{ and time reversal } T \text{ invariance are violated!} \]
$\vec{d}$: 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 $\mathcal{T}(\equiv \mathcal{CPT})$
Symmetries in Standard Model

<table>
<thead>
<tr>
<th></th>
<th>electro-mag.</th>
<th>weak</th>
<th>strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>✓</td>
<td>⊥</td>
<td>✓</td>
</tr>
<tr>
<td>$P$</td>
<td>✓</td>
<td>⊥</td>
<td>✓</td>
</tr>
<tr>
<td>$T \xrightarrow{CPT} CP$</td>
<td>✓</td>
<td>(⊥)</td>
<td>(✓)</td>
</tr>
</tbody>
</table>

- $C$ and $P$ are maximally violated in weak interactions (Lee, Yang, Wu)
- $CP$ violation discovered in kaon decays (Cronin, Fitch) described by CKM-matrix in Standard Model
- $CP$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lesssim 10^{-10}$ (strong $CP$-problem)
Symmetries

- EDM requires violation of symmetries
- but particles may have large magnetic dipole moment (MDM),
- for structureless particles theory even predicts that

$$\mu = g \frac{e \hbar |\vec{S}|}{2m \hbar}$$

with $g = 2$ in leading order

$$G = \frac{g - 2}{2}$$

for various particles:

<table>
<thead>
<tr>
<th></th>
<th>experiment</th>
<th>theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>1 159 652 180.73 (0.28) $\cdot 10^{-12}$</td>
<td>1 159 652 181.13 (0.86) $\cdot 10^{-12}$</td>
</tr>
<tr>
<td>muon</td>
<td>1 165 920.80(54)(33) $\cdot 10^{-9}$</td>
<td>1 165 918.28(49) $\cdot 10^{-9}$</td>
</tr>
<tr>
<td>proton</td>
<td>1.792847356(23)</td>
<td>2*</td>
</tr>
</tbody>
</table>

*: static quark model, SU(6) wave function
\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- Spin
- orbital angular momentum
- quarks
- gluons
- quarks
- gluons
Why is it interesting?
We are surrounded by matter (and not anti–matter)
\[ \eta = \frac{n_B - n_{\bar{B}}}{n_{\gamma}} = 6 \times 10^{-10} \]

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

Starting from equal amount of matter and anti-matter at the Big Bang, from \( CP \)-violation in Standard Model we expect only \( 10^{-18} \)

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
What do we know about EDMs?
History of Neutron EDM

Neutron EDM Upper Limit [pcm]

<table>
<thead>
<tr>
<th>Year of Publication</th>
<th>Standardmodel Predictions</th>
<th>Supersymmetry Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- ORNL, Harvard
- MIT, BNL
- LNPI
- Sussex, RAL, ILL
What do we know about EDMs?

charged particle EDM measurements less precise.

To measure EDMs one needs large electric fields.

Charged particles are accelerated by electric fields.
What do we know about EDMs?

- no EDM observed yet, only limits
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
- no direct measurement for proton
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
- no direct measurement for proton
- Standard Model value essentially 0
What do we know about EDMs?

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

- Charged particle EDM measurements less precise

![Graph showing EDM measurements for various particles](image-url)
What do we know about EDMs?

- Charged particle EDM measurements less precise
- To measure EDMs one needs large electric fields. Charged particles are accelerated by electric fields.
What do we know about EDMs?

Charged Hadron EDM measurements
- First measurement of deuteron, $^3$He EDM,
- first direct measurement of proton EDM
ultimately with a precision of $10^{-29}$ e cm
How to measure charged particle EDMs?
Measurement of charged particle EDMs

Generic 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:

\[
\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}
\]
Spin Motion is governed by Thomas-BMT equation (Bargmann, Michel, Telegdi)

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}
\]

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

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

\(\vec{d}\): electric dipole moment
\(\vec{\mu}\): magnetic moment, \(g\):\(g\)-factor, \(G\): anomalous magnetic moment
\(\gamma\): Lorentz factor
Thomas-BMT equation

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

Several Options (try to get rid terms \( \propto G \)):
Thomas-BMT equation

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

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

1. **Pure electric ring**
   
   with \( \left( G - \frac{1}{\gamma^2 - 1} \right) = 0 \), works only for \( G > 0 \)
Thomas-BMT equation

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

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

1. **Pure electric ring**
   
   with \( \left( G - \frac{1}{\gamma^2 - 1} \right) = 0 \), works only for \( G > 0 \)

2. **Combined \( \vec{E}/\vec{B} \) ring**

   \[ G\tilde{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} = 0 \]
$\tilde{\Omega} = \frac{\hbar}{mc}[G\tilde{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{v} \times \vec{B})]$ 

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

1. **Pure electric ring**
   with $\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$, works only for $G > 0$

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

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

\[ G = \frac{g-2}{2} \]

<table>
<thead>
<tr>
<th></th>
<th>( p/\text{GeV/c} )</th>
<th>( E_R/\text{MV/m} )</th>
<th>( B_V/\text{T} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>1.79</td>
<td>0.701</td>
<td>10</td>
</tr>
<tr>
<td>deuteron</td>
<td>-0.14</td>
<td>1.0</td>
<td>-4</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>-4.18</td>
<td>1.285</td>
<td>17</td>
</tr>
</tbody>
</table>

Ring radius \( \approx 40\text{m} \)
Smaller ring size possible if \( B_V \neq 0 \) for proton

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

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

- Magnetic field (down)
- Magnetic steering
- Electric defocus (horz)
- Electric focus (horz)
- Electric bend field
- Utility straight
- Vertical tune modulating electric quad
- Magnetometers
- Injection straight
- Polarimetry + RF straight

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

Under discussion at Forschungszentrum 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 $p = 0.3 - 3.7\text{GeV}/c \Rightarrow \text{Ideal starting point}$
3. Pure Magnetic Ring

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

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-$\parallel$. 

$$\tilde{E}^* = \tilde{v} \times \tilde{B}$$
3. Pure Magnetic Ring

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

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% \( \dot{s}_d = \bigotimes \)

50% \( \dot{s}_d = \bigcirc \)

\( \vec{E}^* \) field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect
3. Pure Magnetic Ring

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

**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-\( \parallel \).

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

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

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

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

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

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
\[ \Rightarrow \text{net EDM effect can be observed!} \]
Horizontal spin motion $\propto G$  \hspace{1cm} \text{vertical spin motion} \ s_\perp \propto d$
### Summary of different options

<table>
<thead>
<tr>
<th>1.) pure electric ring (BNL)</th>
<th>no $\vec{B}$ field needed</th>
<th>works only for $p$</th>
</tr>
</thead>
<tbody>
<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>
</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>
</tr>
</tbody>
</table>
Statistical Sensitivity

\[ \sigma \approx \frac{\hbar}{\sqrt{N f T \tau_p P E A}} \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>electric field</td>
<td>10 MV/m</td>
</tr>
<tr>
<td>(P)</td>
<td>beam polarization</td>
<td>0.8</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>(\tau_p)</td>
<td>spin coherence time</td>
<td>1000 s</td>
</tr>
<tr>
<td>(T)</td>
<td>running time per year</td>
<td>(10^7) s</td>
</tr>
</tbody>
</table>

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

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

(BNL proposal)
Electrostatic Deflectors

- Electrostatic deflectors from Fermilab (±125kV at 5 cm ≈ 5MV/m)
- Large-grain Nb at plate separation of a few cm yields ≈ 20MV/m
Wien filter

Conventional design
R. Gebel, S. Mey (FZ Jülich)

stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)
Polarimeter

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

d+C elastic, 270 MeV

Cross Section & Analyzing Power for deuterons


FOM = $\sigma A^2$

 CSL available at COSY
desired range
Spin Coherence Time (SCT)

**Short** Spin Coherence Time

\[ \vec{s} \]
\[ \vec{p} \]
Spin Coherence Time (SCT)

Large Spin Coherence Time

\[ \vec{s} \]

\[ \vec{p} \]
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 \( \approx 200 \text{s} \) already reached

(Ed. Stephenson)
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 $d = 10^{-29}$ e·cm in a field of $E = 10$ 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 $\approx 5 \cdot 10^{-5}$ T)

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

- **JEDI** = Jülich Electric Dipole Moment Investigations
- \( \approx 80 \) members
  (Aachen, Dubna, Ferrara, Ithaca, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, ...)
- \( \approx 10 \) PhD students
Storage Ring EDM Efforts

Common R&D work
- Spin Coherence Time
- Beam position monitors (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!
Summary
Summary

- EDM of charged particles can be measured in storage rings.
- EDMs of elementary particles 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
Sources of $CP$ violation

- leptons
- nucleons
- nuclei
- atoms
- molecules
- atomic theory
- nuclear interaction
- QCD

It is mandatory to measure EDM of many different particles to disentangle various sources of $CP$ violation.
It is mandatory to measure EDM of many different particles to disentangle various sources of $CP$ violation.