Measurement of Permanent Electric Dipole Moments of Proton, Deuteron and Light Nuclei in Storage Rings

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on behalf of the JEDI collaboration

SSP2012, Groningen June, 2012
Electric Dipole Moments (EDMs)

- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure it?
What is it?
Electric Dipole Moments: What is it?

- EDM: Permanent spatial separation of positive and negative charges
- Water molecule: \( d = 2 \cdot 10^{-9} \text{e} \cdot \text{cm} \)

Water molecule can have large dipole moment because ground state has two degenerate states of different parity

This is not the case for proton. Here the existence of a permanent EDM requires both \( \mathcal{T} \) and \( \mathcal{P} \) violation, i.e. assuming \( CPT \) invariance this implies \( CP \) violation:

That makes it interesting!
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment

$\mathcal{T}$ violation $\xrightarrow{CPT} \mathcal{CP}$ violation
Why is it interesting?
Why is it interesting?

- $CP$ violation of Standard Model predicts Proton EDM $< 10^{-31} \text{e}\cdot\text{cm}$
- This corresponds to a separation of two $u$–quarks from a $d$–quark by $\approx 10^{-30} \text{cm}$, i.e. $10^{-17}$ of the proton radius!
- Not reachable experimentally in foreseeable future
- Extensions of Standard Model predict EDM as large as $10^{-24} \text{e}\cdot\text{cm}$
- Sources of $CP$ outside the realm of SM are needed to explain matter/anti-matter imbalance in universe
What do we know about (hadron) EDMs?
### What do we know about (hadron) EDMs?

<table>
<thead>
<tr>
<th>Particle/Atom</th>
<th>Current Limit/e·cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>$&lt; 3 \cdot 10^{-26}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$&lt; 3.1 \cdot 10^{-29}$</td>
</tr>
<tr>
<td>$\rightarrow$ Proton</td>
<td>$&lt; 7.9 \cdot 10^{-25}$</td>
</tr>
<tr>
<td>Deuteron</td>
<td>?</td>
</tr>
<tr>
<td>$^{3}$He</td>
<td>?</td>
</tr>
</tbody>
</table>

- Direct measurement only for neutron
- Proton deduced from atomic EDM limit
- No measurement for deuteron (or other nuclei)
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
Sources of $CP$ violation

$CP$ can have different sources

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

⇒ It is important to measure neutron and proton and deuteron and . . . EDMs in order to disentangle various sources of $CP$ violation.
How to measure it?
How to measure it?

**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:

$$\frac{d\vec{s}}{dt} \propto \vec{d} \times \vec{E}$$

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

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

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

Several Options:
“Thomas-BMT” formula

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

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

Several Options:

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

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

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Several Options:

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

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

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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

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

<table>
<thead>
<tr>
<th></th>
<th>( g-2 )</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>
<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)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.
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 $p = 0.3 - 3.7\text{GeV/c}$ ⇒ Ideal starting point
3. Pure Magnetic Ring

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

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

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

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

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

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

\[ \vec{s} \]

\[ \vec{p} \]

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

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

\[ \vec{E}^* \]

\( E^* \) field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect
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 components is $\parallel$ to momentum, 50% of the time it is anti-$\parallel$.

$\vec{E}^\ast = \vec{v} \times \vec{B}$

$E^\ast$ 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 ($\vec{E} + \vec{v} \times \vec{B} = 0$):
$E^\ast = 0 \rightarrow$ part. trajectory is not affected but $B^\ast \neq 0 \rightarrow$ mag. mom. is influenced

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

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

| 2. combined ring       | works for $p, d, {^3}\text{He}$, … | both $\vec{E}$ and $\vec{B}$ required |
| (Jülich)               |                            |                      |

| 3. pure magnetic ring  | existing (upgraded) COSY ring can be used, shorter time scale | lower sensitivity |
| (Jülich)               |                            |                      |
Statistical Sensitivity

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

<table>
<thead>
<tr>
<th>Parameter</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)
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:

$$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} \text{eV}}{3.1 \cdot 10^{-8} \text{eV/T}} \approx 3 \cdot 10^{-17} \text{T}$$

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) $\approx 1000\text{s}$
- Beam positioning $\approx 10\text{nm}$ (relative between CW-CCW)
- Polarimetry on 1 ppm level
- Field Gradients $\approx 10\text{MV/m}$
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

d+C elastic, 270 MeV

available at COSY
desired range

FOM = $\sigma A^2$
Polarimeter

Available at COSY for tests:
EDDA polarimeter
Results on Spin Coherence Time (SCT)

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

⇒ SCT of ≈ 200s already reached

(Ed. Stephenson)
pEDM at Brookhaven

Time-lines:

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-2014</td>
<td>R&amp;D preparation</td>
</tr>
<tr>
<td>2014</td>
<td>final ring design</td>
</tr>
<tr>
<td>2015-2017</td>
<td>ring/beam-line construction</td>
</tr>
<tr>
<td>2017-2018</td>
<td>Installation</td>
</tr>
</tbody>
</table>
Stepwise approach of JEDI project in Jülich

JEDI = Jülich Electric Dipole Moment Investigation
(Collaboration since March 2012, ≈ 70 members, still growing)

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spin coherence time studies</td>
<td>COSY</td>
</tr>
<tr>
<td></td>
<td>Systematic Error studies</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>COSY upgrade</td>
<td>COSY</td>
</tr>
<tr>
<td></td>
<td>first direct measurement at $10^{-24} \text{e} \cdot \text{cm}$</td>
<td>COSY</td>
</tr>
<tr>
<td>3</td>
<td>Build dedicated ring for $p,d$ and $^3\text{He}$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>EDM measurement</td>
<td>Dedicated ring</td>
</tr>
<tr>
<td></td>
<td>at $10^{-29} \text{e} \cdot \text{cm}$</td>
<td></td>
</tr>
</tbody>
</table>

Time scales:
- Steps 1 and 2 <5 years
- Steps 3 and 4 >5 years
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)
EDM of (charged) hadrons are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe.

Measurements of p,d and $^3\text{He}$ needed in addition to neutron efforts at Brookhaven and Jülich to perform such measurements.
EDM Workshop at ECT* Trento

EDM Searches at Storage Rings
October 1-5, 2012
http://www.ectstar.eu

Organizers:
Frank Rathmann (Jülich)
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Andreas Wirzba (Jülich)

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William Marciano (BNL)
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