Storage Ring Based EDM Search
Achievements and Goals

October 20, 2014 | Andreas Lehrach
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on behalf of the JEDI collaboration
(Jülich Electric Dipole Moment Investigations)
Outline

Introduction

Motivation for EDM measurements

EDM Measurements in Storage Rings

Principle and methods

Achievements:
- very precise spin tune measurement
- long spin coherence time (SCT)

R&D work for dedicated storage rings

Summary / Outlook
Electric Dipole Moments

\( \vec{d} \): EDM

\( \vec{\mu} \): magnetic moment

both \( \parallel \) to spin

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

\[
T : \quad H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}
\]

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

It is important to measure neutron and proton and deuteron, light nuclei EDMs in order to disentangle various sources of CP violation.

EDMs are candidates to solve mystery of matter-antimatter asymmetry
Spin Precession with EDM

Equation for spin motion of relativistic particles in storage rings for $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$.

The spin precession relative to the momentum direction is given by:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = \frac{q}{m} \left\{ GB + \left( G - \frac{1}{\gamma^2 - 1} \right) \left( \vec{v} \times \vec{E} \right) + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right\}.$$  

Magnetic Moment  Electric Dipole Moment

$$G = \frac{g - 2}{2}, \quad \bar{\mu} = 2(G + 1) \frac{q}{2m} \bar{S}, \text{ and } \vec{d} = \eta \frac{q}{2m} \bar{S}.$$
Search for Electric Dipole Moments

Approach: EDM search in time development of spin in a storage ring:

\[ \vec{\omega}_G = 0 \]

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

"Freeze" horizontal spin precession; watch for development of a vertical component!

A *magic* storage ring for protons (electrostatic), deuterons, and helium-3

<table>
<thead>
<tr>
<th>particle</th>
<th>p (GeV/c)</th>
<th>E (MV/m)</th>
<th>B (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>0.701</td>
<td>16.789</td>
<td>0.000</td>
</tr>
<tr>
<td>deuteron</td>
<td>1.000</td>
<td>-3.983</td>
<td>0.160</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>1.285</td>
<td>17.158</td>
<td>-0.051</td>
</tr>
</tbody>
</table>

One machine with \( r \sim 30 \text{ m} \)
Storage Ring EDM Project

... measure for buildup of vertical polarization

\[ \Leftrightarrow \]

EDM

Step wise:
COSY (PoF-3)
R&D and Precursor Expt.

Dedicated SR (after PoF-3)
Goal: \(10^{-29}\) e\(\cdot\)cm

Challenges:
- Huge E-fields
- Shielding B-fields
- Spin coherence
- Beam position
- Polarimetry

~ 100 members
(Aachen, Bonn, Dubna, Ferrara, Cornell, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, . . . )

12 PhD students from JARA-FAME (Forces and Matter Experiments)
Experimental Setup for R&D at COSY

- Inject and accelerate vertically polarized deuterons
- Flip spin with help of a RF fields into horizontal plane
- Extract beam slowly (in 100 s) on target
- Measure asymmetry and determine spin precession

**RF Solenoid & RF ExB for Spin Manipulations**

**EDDA polarimeter**

**Sextupole magnets**

**Electron Cooler**

**Polarimeter**
Spin Tune Measurements

Spin vector precesses with $f_{\text{Spin}} = \nu f_{\text{rev}}$ in the horizontal plane.

Asymmetry given by:

$$\epsilon_V(t) = \frac{N_u - N_d}{N_u + N_d} \approx A P(t) \sin(2 \pi \nu f_{\text{rev}} t + \phi)$$

What do we expect?

- Deuterons, $p = 0.97 \text{ GeV}/c$; $\nu \approx 0.16$, $f_{\text{rev}} = 750 \text{ kHz}$
- Spin precession frequency: $\nu \cdot f_{\text{rev}} \approx 125 \text{ kHz}$
- Detector rates: 5 kHz
- Only every 25th spin revolution is detected
  → No direct fit is possible

Example: every 2nd spin precession is detected
**Event Mapping**

- **Mapping the events:**
  - Assume Spin Tune $\nu_{\text{assumed}}$
    - $T_{\text{assumed}} = \frac{2\pi}{\nu_{\text{assumed}} f_{\text{rev}}}$
  - Map all events of a macroscopic time interval (2s) in first period:
    - $t' = \text{mod}(t, T_{\text{assumed}})$
  - Fit asymmetry to first period

- Extract amplitude $A \propto \text{Polarisation}$

\[
\chi^2/\text{ndf} = \frac{18.4}{17}
\]

\[
A = 0.27 \pm 0.01
\]

\[
\phi_0 = 1.36 \pm 0.04
\]

\[
f(\phi_s) = A \cdot \sin(\phi_s + \phi_0)
\]
Assumed Spin Tune vs. Amplitude

- set $\nu_s = \nu_{\text{max}}$ and determine phase in macroscopic time bins of 2s
  $\rightarrow$ $\nu_{\text{max}}$ correct spin tune in the macroscopic time intervals of 2sec
- $\nu_{\text{max}} = 0.160975 \pm 10^{-6}$ $\rightarrow$ allows for $\sigma_s \approx 10^{-6}$
- now fix spin tune and observe phase vs. time
Spin Phase vs. Time

\[ \nu_s = \nu_{\text{assumed}} \]

\[ \nu_s = \nu_{\text{assumed}} + \Delta \nu \]
Spin Phase vs. Time

• 1st derivative gives deviation from assumed spin tune
Spin Tune Measurement

- Spin tune $\nu_s$ can be determined to $10^{-8}$ in 2 s
- Average $\nu_s$ in cycle (100 s) determined to $10^{-10}$
- $\nu_s \approx \gamma G$ varies within one cycle and from cycle to cycle by $10^{-8}$
Spin Coherence Time (SCT)

- Statistical sensitivity of EDM proportional to SCT
- Spin precession with \( f_s = \gamma G f_{\text{ref}} \approx 125 \text{ kHz} \)
- Momentum spread leads to different precession frequencies

- Loss of horizontal polarization ↔ spin decoherence
Spin Coherence Time (SCT)

$\Delta p/p_0$ (different MXG settings)

Sextupole setting
- $\text{MXG} = -1.44\%$
- $\text{MXG} = 7.44\%$
- $\text{MXG} = 11.44\%$
- $\text{MXG} = 19.44\%$

Preliminary

Polarization fit:

$p = p_0 e^{-\tau/\tau_{SCT}}$

Best Spin Coherence Time: $\tau_{SCT} \approx 400\text{s}$
Precursor Experiments:
Resonance Method with „magic“ RF Wien filter

Avoids coherent betatron oscillations of beam. Radial RF-E and vertical RF-B fields to observe spin rotation due to EDM. Approach pursued for a first direct measurement at COSY.

\[ E^* = 0 \Rightarrow E_R = -\beta \times B_y \]

„Magic RF Wien Filter“
no Lorentz force
\[ \rightarrow \text{Indirect EDM effect} \]

Observable:
Accumulation of vertical polarization during spin coherence time

Investigation of sensitivity and systematic limitations

See talk by A. Saleev, S. Mey and S. Chekmenev
Storage Ring EDM Project

Options:

- All-electric ring (proton, electron): only E-field
- All-in-one ring (proton, deuteron, \(^3\)He): E- and B-fields

Challenges:

- Huge E-fields
- Shielding B-fields
- Spin coherence
- Beam position
- Polarimetry

(...)

srEDM Collaboration - JEDI Collaboration

Dedicated precision storage ring

Courtesy R. Talman (Cornell)
# R&D Activities

<table>
<thead>
<tr>
<th>R&amp;D Activity</th>
<th>Goal</th>
<th>Place / Status</th>
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</thead>
<tbody>
<tr>
<td>Internal Polarimeter</td>
<td>spin as a function of time</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td></td>
<td>Systematic errors &lt; 1 ppm</td>
<td></td>
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<tr>
<td></td>
<td>Full-scale polarimeter</td>
<td></td>
</tr>
<tr>
<td>Spin Coherence Time</td>
<td>&gt;$10^3$ s</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td>Beam Position Monitor</td>
<td>resolution 10 nm, 1 Hz BW</td>
<td>CW-CCW beams: RHIC IP</td>
</tr>
<tr>
<td></td>
<td>64 BPMs, $10^7$ s measurement time</td>
<td>Single beams: COSY</td>
</tr>
<tr>
<td></td>
<td>→1 pm (stat.) relative position for single and dual beams (CW-CCW)</td>
<td></td>
</tr>
<tr>
<td>E/B-field Deflector</td>
<td>17 MV/m 2 cm plate separation, 0.15-0.5T</td>
<td>Jülich</td>
</tr>
<tr>
<td>Spin tracking</td>
<td>Symplectic tracking with RF fields and EDM spin kick</td>
<td>Many places</td>
</tr>
</tbody>
</table>
EDM: Prototyping and Spin Physics

- RF ExB Spin Flipper
- Electrostatic Deflector
- SQUID BPM
- Prototype Polarimeter
- Polarized Ion source
- Siberian Snake
- Beam and Spin Dynamics
Utilized Simulation Programs at Jülich

COSY Infinity (MSU) and MODE (StPSU):

• based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle
• including higher-order nonlinearities, normal form analysis, and symplectic tracking
• an MPI version of COSY Infinity is running on the Jülich supercomputer

• Bench marking with “analog computer” Cooler Synchrotron COSY and other simulation codes
Summary and Outlook

Achievements:
- Spin tune measurement with precision of $10^{-10}$ in a single cycle
- Long spin coherence time of roughly 400s
- Several spin tracking codes developed

Goals:
- Continue R&D work at COSY
- Pre-cursor experiment at COSY
- R&D work and design study for dedicated EDM storage ring (CDR end of 2018)

See talks by A. SALEEV, S. MEY and S. CHEKMENEV