Recent Progress of the Storage Ring EDM Search with the JEDI Collaboration

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Motivation

Baryon Asymmetry Problem

<table>
<thead>
<tr>
<th></th>
<th>Standard Model</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{n_B - n_{\bar{B}}}{n_\gamma}$</td>
<td>$\approx 10^{-18}$</td>
<td>$6 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Preconditions needed to explain it:

- Baryon number violation
- **C and CP violation**
- Thermal non-equilibrium in the early Universe

Sakharov (1967)
Motivation
Baryon Asymmetry Problem

- **Electroweak sector** (CKM matrix well established)
  → First observation: 1964 - decay of the neutral K meson

- **Strong Interactions** (so called $\theta$-term)
  → Not observed experimentally yet (it is very small)
  → Strong CP puzzle

  \[ \downarrow \]

  Predictions orders of magnitude too small to explain the observed matter-antimatter asymmetry!

New sources of CP violation Beyond Standard Model needed!

They can manifest in **Electric Dipole Moments** of particles
Motivation
Electric Dipole Moment

Classically

• Charge $\times$ displacement

In Quantum Mechanics

Operator $\mathbf{d} = q\mathbf{r}$

Only available quantization axis is the spin $\mathbf{s} = s\mathbf{\sigma}$

(there can be only one vector in a quantum system)

$\mathbf{d} = d\mathbf{\sigma}$

• $\mathbf{d} \parallel \mathbf{\sigma}$ and $\mathbf{\mu} \parallel \mathbf{\sigma}$ (magnetic moment)
EDM – CP violation

The observable quantity:
• Energy of electric dipole in electric field
• Energy of magnetic dipole in magnetic field

\[ H = H_E + H_M = - \mu \sigma \cdot B - d \sigma \cdot E \]

T: \[ H = - \mu \sigma \cdot B + d \sigma \cdot E \]
P: \[ H = - \mu \sigma \cdot B + d \sigma \cdot E \]

H violates T and P symmetry if \( d \neq 0 \)

T violation → CP violation (since CPT conserved)
The graph shows the electron magnetic dipole moment (edm) values for various particles, with the y-axis representing edm/e cm and the x-axis listing particles and their corresponding edm values.

- Electron (Ybf, ThO): $10^{-39}$
- Muon: $10^{-37}$
- Tau: $10^{-35}$
- Neutron: $10^{-33}$
- Proton ($^{199}$Hg): $10^{-31}$
- Lambda ($\Lambda$): $10^{-29}$

The Standard Model (QCD = 0) edm value is also indicated on the graph.
Upper limits
Upper limits

- SUSY ($\frac{\alpha}{\pi} < \varphi_{CP} < 1$)
- Standard Model ($\theta_{QCD} = 0$)
- Electron (YbF, ThO)
- Neutron
- Proton ($^{199}$Hg)
- Deuteron
Measurement principle

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

Simplified case:

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

Build-up of vertical polarization by slow precession

Extremely small effects!

With edm \( \sim 10^{-29} \text{e} \cdot \text{cm} \)

effect of the order of \( \mu \text{deg/hour} \)

“Frozen spin”
Thomas-BMT equation:

In storage rings (magnetic field – vertical, electric field - radial)

\[
\frac{d\hat{S}}{dt} = \hat{\Omega} \times \hat{S} = -\frac{q}{m_0} \left\{ GB \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\hat{\beta} \times \hat{E}}{c} + d \frac{m_0}{q\hbar S} (\hat{E} + c\hat{\beta} \times \hat{B}) \right\} \times \hat{S}
\]

**Magnetic moment** causes fast spin precession in horizontal plane

- **\( \Omega \):** angular precession frequency
- **\( G \):** anomalous magnetic moment
- **\( d \):** electric dipole moment
- **\( \gamma \):** Lorentz factor
Measurement
Pure magnetic ring

\[
\frac{d\mathbf{S}}{dt} = \mathbf{\Omega} \times \mathbf{S} = -\frac{q}{m_0} \left\{ G \mathbf{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\mathbf{\beta} \times \mathbf{E}}{c} + d \frac{m_0}{q\hbar S} \left( \mathbf{E} + c\mathbf{\beta} \times \mathbf{B} \right) \right\} \times \mathbf{S}
\]

**COSY**: pure magnetic ring, polarized protons and deuterons
access to EDM via motional electric field \(\mathbf{\beta} \times \mathbf{B}\)

Starting point for a proof-of-principle experiment
EDMs of charged hadrons: p, d

R&D with deuterons
\[ p = 1 \text{ GeV/c} \]
\[ G = -0.14256177(72) \]
\[ v_s \approx -0.161 \rightarrow f \approx 120 \text{ kHz} \]

Study spin tune \[ v_s = \frac{\sqrt{G}}{|\Omega|} = \gamma G \]

\[ \rightarrow \text{phase advance per turn} \]

Research and Development at COSY

http://collaborations.fz-juelich.de/ikp/jedi/
Research and Development at COSY

- Measurement of fast precessing polarization
- Precise determination of spin tune
- Spin coherence time
- Phase lock of spin precession

- Dedicated polarimetry → D. Shergelashvili (HK 36.6) and F. Müller (HK 36.7) talks
- Beam instrumentation → F. Abusaif (HK 41.3) talk

- Wien filter commissioning
- Database for future polarimetry
Measurement in COSY
Pure magnetic ring

- Magnetic Dipole Moment
  - fast horizontal precession

- Electric Dipole Moment
  - very slow vertical precession

$E^*$ field tilts spin due to EDM
- 50% of time up
- 50% of time down

$$\frac{dS}{dt} \propto \left[ G\vec{B} + d \frac{m_0 c}{q\hbar S} \vec{\beta} \times \vec{B} \right] \times \vec{S}$$

Horizontal precession angular velocity $\omega_{\alpha}$

Vertical spin direction $\beta$

No vertical polarisation build-up

Tiny oscillation
Measurement
RF Wien Filter method

Wien Filter: introduces B and E field oscillating with radio frequency
Lorentz force vanishes: no effect on EDM rotation
**Effect: Adds extra horizontal precession**

Wien Filter has to be always **in phase** with the horizontal spin precession!

**Feedback system developed and tested:** Phys. Rev. Lett., 119, 014801 (2017)
Resonant frequency controlled, precession of spin phase locked
Wien Filter Commissioning
Wien Filter Commissioning – 90° mode

Spin rotations with phase lock

\[ \varphi(t) = 2\pi \nu_s f_c t \]
\[ B_{WF}(t) = B_0 \sin(\omega t + \Delta\varphi) \]

Task: maintain \( \omega = 2\pi |k + \nu_s| f_c \)
and fix \( \Delta\varphi \)
→ Controlled via WF frequency

Spin build-up as a function of phase \( \sim \sin\Delta\varphi \) → Feedback system works properly!
We see vertical polarization buildup → EDM-like signal

Two systematic contributions:

1. Residual, radial magnetic field from WF
   → effect equivalent to WF rotation

2. Field imperfections in COSY
   → transverse contribution: equivalent to WF rotation
   → longitudinal contribution: equivalent to additional static solenoid field

The measurement shows the stability of COSY conditions within 24 hours
**Polarimetry – database experiment**

Reaction: dC elastic scattering

Up/Down asymmetry \( \propto \) horizontal component of polarization \( P_x \)
Right/Left asymmetry \( \propto \) vertical component of polarization \( P_y \)

\[
\sigma^{pol}(\theta, \phi) = \sigma_0(\theta)[1 + \frac{3}{2}PA_y(\theta)\cos \phi]
\]

\[
PA_y(\theta) = \frac{\sigma^L(\theta) - \sigma^R(\theta)}{\sigma^L(\theta) + \sigma^R(\theta)}
\]

**EDDA detector**

- Range Hodoscope: 3 x 24 elements (10cm)
- Window Counter: 2 x 24 elements (3mm) pizza shaped
- Straw Tubes: 4 x 4 layers, 0°, 90°, 45°, -45°
- Veto Hodoscope: 1 x 48 elements (5mm) pizza shaped

**Target position**
- 3°-18°

**Spin**
- y

**Beam pipe**
- z

**Target**
- x

**Beam**
- 9°-13°
Polarimetry – database experiment

Motivation: database to produce realistic Monte Carlo simulations of detector responses for a polarimeter designed for EDM

Goal: $A_y, A_{yy}, d\sigma/d\Omega$ for
→ $dC$ elastic scattering
→ main background reactions (deuteron breakup)

Beamtime in November 2016 (2 weeks)

d energies: 170, 200, 235, 270, 300, 340, 380 MeV
Targets: C and CH$_2$

Beam polarization: 5 polarization states
$(P_y, P_{yy}) = (0,0), (-\frac{2}{3},0), (\frac{2}{3},0), (\frac{1}{2}, -\frac{1}{2}), (-1, 1)$

Setup: Modified WASA Forward Detector
Polarimetry – database experiment

→ Full $\varphi$ coverage
→ $\theta$ range $4^\circ$ - $17^\circ$

Range Hodoscope:
- 3 x 24 elements (10cm)
- 2 x 24 elements (15cm)
pizza shaped

Veto Hodoscope:
- 1 x 24 elements (20mm)
vertical bars
double-sided readout

Window Counter:
- 2 x 24 elements (3mm)
pizza shaped

Straw Tubes:
- 4 x 4 layers
$0^\circ, 90^\circ, 45^\circ, -45^\circ$

Trigger Hodoscope:
- 1 x 48 elements (5mm)
pizza shaped
Polarimetry – database experiment

\[ \frac{3}{2} \text{PA}_y \]

\( \Theta_{\text{lab}} [\text{deg}] \)

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C by Y. Satou et al.

Preliminary
Polarimetry – database experiment

![Graph showing data points and curves for different energy levels of dC Elastic scattering.](image)
Conclusions

• EDMs of elementary particles key for understanding sources of CP violation → explanation of matter – antimatter imbalance

• Principle of experiments – measurements of spin precession in magnetic field
• EDM of charged particles measured in storage rings

• COSY: ideal starting point for R&D and a pre-cursor experiment with Wien Filter method
Backup
Fundamental Discrete Symmetries

A physical model is symmetric under a certain operation → if its properties are invariant under this operation

- T-symmetry: \( t \rightarrow -t \)
- P-symmetry: \( r \rightarrow -r \)
- C-symmetry: particle-antiparticle interchange
- CPT conserved

<table>
<thead>
<tr>
<th>Physical Quantity</th>
<th>C</th>
<th>P</th>
<th>T</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric field ( E )</td>
<td>-E</td>
<td>-E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Magnetic field ( B )</td>
<td>-B</td>
<td>B</td>
<td>-B</td>
<td>-B</td>
</tr>
<tr>
<td>Momentum ( p )</td>
<td>p</td>
<td>-p</td>
<td>-p</td>
<td>-p</td>
</tr>
<tr>
<td>Angular momentum ( l )</td>
<td>l</td>
<td>l</td>
<td>-l</td>
<td>l</td>
</tr>
<tr>
<td>Charge density ( q )</td>
<td>-q</td>
<td>q</td>
<td>q</td>
<td>-q</td>
</tr>
</tbody>
</table>
EDM – Orders of magnitude

**Neutron** *(udd)*

| Charge | \( | r_1 - r_2 | \) |
|--------|-----------------|
| \( e \) | \( 1 \text{ fm} = 10^{-13} \text{ cm} \) |

**EDM**

- Naive expectation: \( 10^{-13} \text{ e} \cdot \text{ cm} \)
- Observed (upper limit): \( < 3 \cdot 10^{-26} \text{ e} \cdot \text{ cm} \)
- SM prediction:
  - Parity violation: \( \sim 10^{-32} \text{ e} \cdot \text{ cm} \)
  - CP electroweak violation: \( \sim 10^{-32} \text{ e} \cdot \text{ cm} \)

nEDM of \( 10^{-26} \text{ e} \cdot \text{ cm} \) → separation of u from d quarks of \( \sim 5 \cdot 10^{-26} \text{ cm} \)
Motivation
Electric Dipole Moment of proton and deuteron

No direct measurement
Disentangle the fundamental source(s) of EDMs

Experiment
Where is the EDM?
How do we understand it?
Dream
Experimental requirements

High precision storage ring
alignment, stability, field homogeneity

High intensity beams
$N = 4 \times 10^{10}$ per fill

Polarized hadron beams
$P = 0.8$

Large electric fields
$E = 10$ MV/m

Long spin coherence time
$\tau = 1000$ s

Polarimetry
analyzing power $A = 0.6$, acc. $f = 0.005$

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{N f \tau PAE}} \Rightarrow \sigma_{\text{stat}}(1 \text{ year}) \approx 10^{-29} \text{ ecm}$$

Challenge: systematic uncertainties on the same level!

Even in Pure Electric Ring – lots of sources of syst. uncertainties

→ Very small radial B field can mimic an EDM effect

$$\mu B_r \sim dE_r$$
Measurement

Pure electric ring

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0} \left\{ G \vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \vec{\beta} \times \vec{E} \right\} + d \frac{m_0}{q \hbar S} \left( \vec{E} + c \vec{\beta} \times \vec{B} \right) \times \vec{S}
\]

\[\equiv 0!\]

"frozen spin": precession vanishes at magic momentum

\[G = \frac{1}{\gamma^2 - 1} \Rightarrow p = \frac{m}{\sqrt{G}}\]

only possible for \(G > 0\)

Dedicated ring for protons
Storage rings: combined ring

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0} \left\{ G\vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\vec{\beta} \times \vec{E}}{c} + d \frac{m_0}{\hbar S} (\vec{E} + c\vec{\beta} \times \vec{B}) \right\} \times \vec{S}
\]

„frozen spin“: proper combination of $\vec{B}$, $\vec{E}$ and $\gamma$
also for $G < 0$ (i.e. deuterons, $^3\text{He}$)

Combined ring both for protons and deuterons
Polarimetry

Detector signal
\[ N_{up,down}^{\text{up}} = 1 \pm PA \sin(2\pi \cdot f_{\text{prec}} t) \]
\[ = 1 \pm PA \sin(2\pi \cdot v_s n_{\text{turns}}) \]

P: polarisation, A: analysing power

Asymmetry
\[ \varepsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = PA \sin(2\pi \cdot v_s n_{\text{turns}}) \]

Challenges
- precession frequency \( f_{\text{prec}} \approx 120 \text{ kHz} \)
- \( v_s \approx -0.16 \) → 6 turns / precession
- event rate \( \approx 5000 \text{ s}^{-1} \) → 1 hit / 25 precessions
→ no direct fit of the rates
Polarimetry

Detector signal

\[ N_{up,down}^{up,down} = 1 \pm PA \sin(2\pi \cdot f_{prec} t) \]
\[ = 1 \pm PA \sin(2\pi \cdot v_s n_{turns}) \]

P: polarisation, A: analysing power

Asymmetry

\[ \varepsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = PA \sin(2\pi \cdot v_s n_{turns}) \]

Too few polarimeter events to resolve oscillation directly!

Map many events to one cycle
**Polarimetry**

beam revolutions: counting turn number $n$

\[ \downarrow \]

assign turn number $n \rightarrow \text{phase advance } \varphi_s = 2\pi n_s n$

\[ \downarrow \]

for intervals of $\Delta n = 10^6$ turns: $\varphi_s \rightarrow \varphi_s \mod 2\pi$

\[ \downarrow \]

scan $n_s$ in some interval around $n_s = \gamma G$

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**Graphs and Diagrams:**

1. Graph showing asymmetry $\varepsilon$ versus spin phase advance $\varphi_s$.
2. Graph illustrating the maximum asymmetry $\sigma_{n_s} \lesssim 10^{-6}$ and $n_s,\text{max}$. 

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28.02.2018 M. Żurek - JEDI recent results
Spin tune measurement

Monitoring phase of asymmetry with fixed spin tune

\[ \Delta v_s = \frac{d\phi}{dn} \cdot \Delta n \]

\[ \sigma_{\Delta v_s} \approx 10^{-10} \]

\[ v_s = v_{s,\text{true}} + \delta v_s \]

PRL 115, 094801 (2015)
Spin coherence time

At the beginning all spin vectors aligned

After some time spin vectors all out of phase

Polarization vanishes $\rightarrow$ measurement time limited

\[
\frac{\Delta \gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta \nu}{\nu} \quad \Rightarrow \quad \Delta \varphi \approx 60 \text{ rad/s}
\]

* unbunched beam: $\frac{\Delta \gamma}{\gamma} \approx 10^{-5}$ $\Rightarrow$ decoherence in $< 1$ s
* bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1\textsuperscript{st} order $\rightarrow \tau \approx 20$ s
* correcting higher order effects using sextupoles
  and (pre-) cooling $\rightarrow \tau \approx 1000$ s
Spin coherence time

Controlling spin direction

Feedback system

Goal: Maintain resonance frequency and phase between spin precession and Wien filter

→ keep precession frequency stable
→ match frequency and phase to Wien filter

Test at COSY:
control spin tune via COSY rf:
\[ \nu_s = G \gamma \]
control phase to external frequency by accelerating/decelerating spin precession

PRL, 119, 014801 (2017)
Wien Filter Commissioning

Detuned WF: residual Lorentz force

**Tuned WF**: Lorenz force vanishes

**Detuned WF**: residual Lorentz force excites beam at WF frequency

→ Lock-in amplifier connected to BPMs measures amplitude of beam oscillations