SEARCHES FOR ELECTRIC DIPOLE MOMENTS (EDM) AT A STORAGE RING WITH JEDI

17 AUGUST 2018     MARIA ŻUREK FOR THE JEDI COLLABORATION

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**MOTIVATION**

**Baryon Asymmetry Problem**

<table>
<thead>
<tr>
<th>Baryon Asymmetry</th>
<th>Observation</th>
<th>Standard Cosmological Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(N_B - N_{\bar{B}}) / N_\gamma$</td>
<td>$6 \times 10^{-10}$</td>
<td>$\sim 10^{-18}$</td>
</tr>
</tbody>
</table>

Preconditions needed to explain it (Sakharov):
- $\mathcal{C}$ and $\mathcal{C}\mathcal{P}$ violation
- Baryon number violation
- Thermal non-equilibrium in the early Universe

**$\mathcal{C}\mathcal{P}$ violation in Standard Model**

- **Electroweak sector** (CKM matrix well established)
- **Strong interactions** ($\theta$-term, strong-$\mathcal{C}\mathcal{P}$ puzzle)

Predictions orders of magnitude too small to explain the asymmetry!

New sources of $\mathcal{C}\mathcal{P}$ violation can be seen in EDM of particles
ELECTRIC DIPOLE MOMENT

CP-symmetry violation

\[ \vec{d} = \eta \cdot \frac{q}{2mc} \vec{S} \]
\[ \vec{\mu} = g \cdot \frac{q}{2m} \vec{S} \]

Pseudo vectors

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

\[ H = H_M + H_E = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \]
\[ P : H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E} \]
\[ T : H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E} \]

H violates \( \mathcal{T} \) and \( \mathcal{P} \)-symmetry if \( d \neq 0 \)

\( \mathcal{T} \) violation

\( \mathcal{CP} \) violation (\( \mathcal{CPT} \) conserved)
ELECTRIC DIPOLE MOMENT

Current limits

![Graph showing EDM limits for different particles and models with upper limits indicated for SUSY, Standard Model, and various particles like electron, muon, tau, neutron, proton (199Hg), and deuteron.]

- Upper limits

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MOTIVATION

Disentanglement the fundamental source(s) of EDMs

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

- Neutron, Proton
- Nuclei: $^1\text{H}, ^3\text{H}, ^3\text{He}$
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: TI, Cs
- Molecules: YbF, ThO, HFF
- Leptons: muon

atomic theory → nuclear theory → QCD (including $\Theta$-term)

- quark EDM
- quark chromo-EDM
- gluon chromo-EDM
- four-quark operators
- lepton-quark operators
- lepton EDM
PRINCIPLE OF EDM MEASUREMENT

Charged Particles in a Storage Ring

General idea: Observation of EDM interaction with electric field

Simplified case – pure E field:

$d \neq 0$: spin rotation out of horizontal plane

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

Build-up of vertical polarization

$d \propto$ spin rotation angle

EDM $\sim 10^{-29}$ e·cm

Effect of the order of $\mu$deg/hour

Extremely small effects!

“Frozen spin” - Spin parallel to momentum
**EXPERIMENTAL REQUIREMENTS**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
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<tbody>
<tr>
<td>High precision storage ring</td>
<td>alignment, stability, field homogeneity</td>
</tr>
<tr>
<td>Polarized hadron beams</td>
<td>$P = 0.8$</td>
</tr>
<tr>
<td>High intensity beams</td>
<td>$N = 4 \times 10^{10}$ per fill</td>
</tr>
<tr>
<td>Large electric fields</td>
<td>$E = 10$ MV/m</td>
</tr>
<tr>
<td>Long spin coherence time</td>
<td>$\tau = 1000$ s</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>analyzing power $A = 0.6$, acc. $f = 0.005$</td>
</tr>
</tbody>
</table>

\[
\sigma_{\text{stat}} \approx \frac{1}{\sqrt{N f \tau P A E}} \implies \sigma_{\text{stat}}(1 \text{ year}) \approx 10^{-29} \text{ ecm}
\]

**Challenge: systematic uncertainties on the same level!**

Even in Pure Electric Ring – lots of sources of systematic uncertainties

Very small radial $B$ field can mimic an EDM effect: $\mu B_r \sim dE_r$
STORAGE RING EDM MEASUREMENTS

- Only EDM storage ring measurement: muon (parasitic measurement to g-2)

- **Cooler Synchrotron COSY**
  at Forschungszentrum Jülich, Germany
  - magnetic storage ring
  - polarized proton and deuteron beams up to 3 GeV/c

  Ideal **starting point** for proof of principle experiment

EDMs of charged hadrons: p, d

R&D with deuterons

\[ p = 1 \text{ GeV/c} \]
\[ G = -0.14256177(72) \]
\[ f_s \approx 120 \text{ kHz} \]
\[ f_{\text{rev}} \approx 750 \text{ kHz} \]

\[ \nu_s = \frac{\text{spin revolutions}}{\text{turn}} \approx G \gamma \approx -0.16 \]
Thomas-BMT equation:
In storage rings (magnetic field – vertical, electric field - radial)

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

MDM causes fast spin precession in horizontal plane
EDM causes small vertical polarization buildup oscillating up and down
SPIN IN PURELY MAGNETIC RING

50% of time
momentum \uparrow \downarrow \text{spin} \quad \text{Spin tilted up}

50% of time
momentum \downarrow \uparrow \text{spin} \quad \text{Spin tilted down}

no vertical polarisation build-up
					
tiny oscillation

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SPIN IN PURELY MAGNETIC RING

50% of time

momentum ↑ spin  Spin tilted up

50% of time

momentum ↓ spin  Spin tilted down

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

Jülich Electric Dipole moment Investigations (JEDI)

- Precise determination of spin tune

- Spin coherence time

- Phase lock of spin precession

- Wien filter commissioning
- Polarimetry development
- Beam instrumentation
- Spin-tracking simulations

http://collaborations.fz-juelich.de/ikp/jedi/
Scattering from Carbon target

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

Right/Left asymmetry \( \propto \) vertical component of polarization \( P_y \)

\[ c_{LR} = \frac{N_L - N_R}{N_L + N_R} = P_y A_y \]

EDM signal appears here

Up/Down asymmetry \( \propto \) horizontal component of polarization \( P_x \)

\[ c_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y \]

Needed to maintain “frozen spin” condition

Typically \( A_y \sim 0.6 \)
\[ \nu_s = \frac{\text{spin revolutions}}{\text{turn}} \approx G \gamma \approx -0.16 \quad \text{Deuteron spin precesses with } \sim 120 \text{ kHz!} \]

Detector signal and measured asymmetry oscillates

\[ \epsilon_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y \sin(2\pi \cdot f_{\text{prec}}t) = P_x A_y \sin(2\pi \cdot \nu_s n_{\text{turn}}) \]

With event rates \( \sim 5000 \text{ s}^{-1} \) we have \( \sim 1 \text{ hit / 25 precessions} \)

Too few polarimeter events to resolve oscillation directly!

Map events to one cycle

Monitoring phase of asymmetry with fixed spin tune

Relative precision:
Muon (g-2): $\sim 10^{-6}$  
Deuteron (JEDI): $\sim 10^{-9}$

Much longer measurement: 600$\mu$s vs 100 s

Precise determination of $G$ impossible:
Ring imperfections $\rightarrow$ MDM rotations about non-vertical axes
**SPIN COHERENCE TIME**

Beginning of measurement

- All spin vectors aligned
- Polarization vanishes

After some time

- Spin vectors all out of phase
- Measurement time limited
SPIN COHERENCE TIME

Beginning of measurement

All spin vectors aligned

After some time

Spin vectors all out of phase

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

- unbunched beam: \[ \frac{\Delta \gamma}{\gamma} \approx 10^{-5} \] \( \Rightarrow \) decoherence in \( < 1 \text{s} \)

- bunching: eliminate effects on \( \frac{\Delta p}{p} \) in 1\text{st} order \( \Rightarrow \tau \approx 20 \text{ s} \)

- correcting higher order effects using sextupoles and (pre-) cooling \( \Rightarrow \tau \approx 1000 \text{ s} \)
**SPIN COHERENCE TIME**

Beginning of measurement

All spin vectors aligned

After > 1000 s

Spin vectors all out of phase

---

Graph:

- X-axis: Time [s]
- Y-axis: Normalized polarization
- Data points at 0, 200, 400, 600, 800, 1000, 1200, 1400 s with values close to 1, 0.8, 0.6, 0.4, 0.2, 0.1, 0.0, and 0.0 respectively.

**Reference:**

CONTROLLING SPIN DIRECTION

Feedback system

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

1\textsuperscript{st} test at COSY:
control spin tune via COSY rf: \( \nu_s = G \gamma \)

Now:
We change directly Wien filter frequency!

\( \sigma \approx 12^\circ \)

WIEN FILTER COMMISSIONING
Wien Filter Commissioning

EDM Mode

MDM precession
COSY + WF
We see vertical polarization buildup - EDM-like signal
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

Stability of COSY conditions within 24 hours
We see vertical polarization buildup - EDM-like signal

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Stability of COSY conditions within 24 hours
OUTLOOK

2019

COSY

1\textsuperscript{st} deuteron EDM measurement
Sensitivity: $\sim 10^{-19} \text{e}\cdot\text{cm}$

Prototype ring

- Proof of principle
- Test deflectors/instrumentation
- Check lifetime
- Test CW/CCW operation
- Test frozen spin (additional B-field at low energy)

? Dedicated ring

Highly sensitive EDM measurement
SUMMARY

• EDMs of elementary particles key for understanding sources of CP violation
  ⇒ explanation of matter – antimatter imbalance
• Extremely ambitious measurement for charged particles
• Preparations for proof-of-principle experiment at COSY
  ⇒ Extended R&D program
• First measurement of deuteron EDM in progress
THANK YOU!

http://collaborations.fz-juelich.de/ikp/jedi/

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BACKUP
POLARIMETRY FOR AN EDM EXPERIMENT

Challenge: measurement of tiny polarization build-up

For proton EDM $\sim 10^{-29} \, \text{e} \cdot \text{cm}$ and $\sim 1$ year of measurement

$$\Delta \varepsilon_{LR} = \varepsilon_t - \varepsilon_0$$

$$= \Delta P_y A_y \approx 10^{-6}$$

Systematics count!

Polarimetry requirements

Long term reproducibility:

$\rightarrow$ Continuous measurement for a long time

Minimization of asymmetry error:

$\rightarrow$ Maximization of FoM

Figure of Merit

Efficiency $\downarrow$

High $A_y$ $\downarrow$

$\delta \varepsilon_{LR}^{(\text{stat})} \propto \frac{1}{\sqrt{N |A_y|}} = \frac{1}{\sqrt{\text{FoM}}}$

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ACTIVITY AT COSY

Jülich Electric Dipole moment Investigations (JEDI)

R&D with towards first proof-of-principle EDM experiment for deuterons and protons

Polarimetry-group activity:
- Development of dedicated polarimeter based on LYSO crystals
- Database experiment with WASA detector

Motivation:
- Optimal configuration of the polarimeter

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

http://collaborations.fz-juelich.de/ikp/jedi/
DEUTERON DATABASE EXPERIMENT WITH WASA

Detector Setup

**Beamtime in November 2016** (2 weeks)

**Deuteron energies:** 170, 200, 235, 270, 300, 340, 380 MeV

**Nominal beam polarization:** \((P_y, P_{yy}) = (0,0), (-\frac{2}{3},0), (\frac{2}{3},0), (\frac{1}{2}, -\frac{1}{2}), (-1, 1)\)

**Targets:** C and CH\(_2\)

**Setup:** Modified WASA Forward Detector

- Full \(\phi\) coverage
- \(\theta\) range 4° - 17°
DATABASE EXPERIMENT WITH WASA

Analyzing power for elastic dC scattering
POLARIMETRY

Detector signal

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

P: polarisation, A: analysing power

Asymmetry

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

Challenges

- precession frequency \( f_{prec} \approx 120 \) kHz
- \( v_s \approx -0.16 \) \( \rightarrow \) 6 turns / precession
- event rate \( \approx 5000 \) s\(^{-1}\) \( \rightarrow \) 1 hit / 25 precessions
  \( \rightarrow \) no direct fit of the rates
R&D AT COSY

EDMs of charged hadrons: $p$, $d$

R&D with deuterons

$p = 1 \text{ GeV/c}$

$G = -0.14256177(72)$

$\nu_s \approx -0.161 \, f \approx 120 \text{ kHz}$

study spin tune $\nu_s = \frac{|\Omega|}{|\omega_{cyc}|} = \gamma G$

$\rightarrow$ phase advance per turn

WASA polarimeter

EDDA polarimeter

precession

$\vec{d}$

rf solenoid
**WIEN FILTER METHOD**

- **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

\[
\frac{d\vec{S}}{dt} \propto \left( G\vec{B} + \frac{m_0c}{q\hbar S} \vec{\beta} \times \vec{B} \right) \times \vec{S}
\]

- **Horizontal precession angular velocity**
  - No vertical polarisation build-up

- **Vertical spin direction**
  - Tiny oscillation

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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!

Resonant frequency controlled, precession of spin phase locked
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
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The measurement shows the stability of COSY conditions within 24 hours