Electric Dipole Moment Searches using Storage Rings

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(JEDI collaboration)

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6 Summary
**Baryon asymmetry in the Universe**

Carina Nebula: Largest-seen star-birth regions in the galaxy

<table>
<thead>
<tr>
<th>Observation and expectation from Standard Cosmological Model (SCM):</th>
<th>$\eta = (n_b - n_{\bar{b}})/n_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>$(6.11^{+0.3}_{-0.2}) \times 10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>$(5.53 - 6.76) \times 10^{-10}$</td>
</tr>
<tr>
<td>Expectation from SCM</td>
<td>$\sim 10^{-18}$</td>
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<td></td>
<td>Bernreuther (2002) [3]</td>
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Precision frontier

**EDMs possibly constitutes missing cornerstone**

to explain surplus of matter over antimatter in the Universe:

- SCM gets it wrong by about 8 orders of magnitude.

**Large worldwide effort to search for EDMs of fundamental particles:**

- hadrons, solids, atoms and molecules.
- $\sim 500$ researchers (estimate by Harris, Kirch).
- Total of $\approx 20$ talks at Spin 2018 on EDM related R&D.
Introduction

Precision frontier

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Why search for charged particle EDMs using a storage ring?
So far, no direct measurement of charged hadron EDMs:
- potentially higher sensitivity than for neutrons:
  - longer lifetime,
  - more stored polarized protons/deuterons available than neutrons, and
  - one can apply larger electric fields in storage ring.
- Approach complimentary to neutron EDM searches.
- EDM of single particle not sufficient to identify \( CP \) violating source [4]
Naive estimate of scale of nucleon EDM

From Khriplovich & Lamoreux [5]:

- $CP$ and $P$ conserving magnetic moment $\approx$ nuclear magneton $\mu_N$.
  \[ \mu_N = \frac{e}{2m_p} \sim 10^{-14} \text{ e cm}. \]

- A non-zero EDM requires:
  - $P$ violation: price to pay is $\approx 10^{-7}$, and
  - $CP$ violation (from $K$ decays): price to pay is $\sim 10^{-3}$.

In summary:

\[ |d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24} \text{ e cm} \]

In Standard model (without $\theta_{QCD}$ term):

\[ |d_N| \sim 10^{-7} \times 10^{-24} \text{ e cm} \sim 10^{-31} \text{ e cm} \]
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Region to search for BSM physics ($\theta_{QCD} = 0$) from nucleon EDMs:

$$10^{-24} \text{ e cm} > |d_N| > 10^{-31} \text{ e cm}.$$
Status of EDM searches I

**EDM limits in units of [e cm]:**

- Long-term goals for neutron, $^{199}_{80}$Hg, $^{129}_{54}$Xe, proton, and deuteron.
- Neutron equivalent values indicate value for neutron EDM $d_n$ to provide same physics reach as indicated system:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Current limit</th>
<th>Goal</th>
<th>$d_n$ equivalent</th>
<th>date [ref]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$&lt; 8.7 \times 10^{-29}$</td>
<td>$\approx 10^{-29}$</td>
<td></td>
<td>2014 [6]</td>
</tr>
<tr>
<td>Muon</td>
<td>$&lt; 1.8 \times 10^{-19}$</td>
<td></td>
<td></td>
<td>2009 [7]</td>
</tr>
<tr>
<td>Tau</td>
<td>$&lt; 1 \times 10^{-17}$</td>
<td></td>
<td></td>
<td>2003 [8]</td>
</tr>
<tr>
<td>Lambda</td>
<td>$&lt; 3 \times 10^{-17}$</td>
<td></td>
<td></td>
<td>1981 [9]</td>
</tr>
<tr>
<td>Neutron</td>
<td>$(-0.21 \pm 1.82) \times 10^{-26}$</td>
<td>$\approx 10^{-28}$</td>
<td>$10^{-28}$</td>
<td>1981 [9]</td>
</tr>
<tr>
<td>$^{199}_{80}$Hg</td>
<td>$&lt; 7.4 \times 10^{-30}$</td>
<td>$10^{-30}$</td>
<td>$&lt; 1.6 \times 10^{-26}$ [11]</td>
<td>2015 [10]</td>
</tr>
<tr>
<td>$^{129}_{54}$Xe</td>
<td>$&lt; 6.0 \times 10^{-27}$</td>
<td>$\approx 10^{-30}$ to $10^{-33}$</td>
<td>$\approx 10^{-26}$ to $10^{-29}$</td>
<td>2001 [13]</td>
</tr>
<tr>
<td>Proton</td>
<td>$&lt; 2 \times 10^{-25}$</td>
<td>$\approx 10^{-29}$</td>
<td>$10^{-29}$</td>
<td>2016 [12]</td>
</tr>
<tr>
<td>Deuteron</td>
<td>not available yet</td>
<td>$\approx 10^{-29}$</td>
<td>$\approx 3 \times 10^{-29}$ to $5 \times 10^{-31}$</td>
<td>2016 [12]</td>
</tr>
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</table>
Missing are *direct* EDM measurements:

- No direct measurements of electron: limit obtained from (ThO molecule).
- No direct measurements of proton: limit obtained from \( {}^{199}_{80}\text{Hg} \).
- No measurement at all of deuteron EDM.
Experimental requirements for storage ring EDM searches

High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields.
- High beam intensity: \( N = 4 \times 10^{10} \) particles per fill.
- High polarization of stored polarized hadrons: \( P = 0.8 \).
- Large electric fields: \( E = 10 \text{ MV/m} \).
- Long spin coherence time: \( \tau_{\text{SCT}} = 1000 \text{ s} \).
- Efficient polarimetry with
  - large analyzing power: \( A_y \approx 0.6 \),
  - and high efficiency detection \( f \approx 0.005 \).
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In terms of numbers given above:

- This implies:
  \[
  \sigma_{\text{stat}} = \frac{1}{\sqrt{N f \tau_{\text{SCT}} P A_y E}} \quad \Rightarrow \quad \sigma_{\text{stat}}(1 \text{ yr}) = 10^{-29} \text{ e cm}.
  \] (1)

- Experimentalist’s goal is to provide \( \sigma_{\text{syst}} \) to the same level.
Particles with magnetic and electric dipole moment

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$ ($\propto \vec{s}$),

- **non-relativistic Hamiltonian:**
  \[
  H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}.
  \]

- **Energy of magnetic dipole** invariant under $P$ and $T$:
  \[
  P \text{ or } T \quad \Rightarrow \quad -\vec{\mu} \cdot \vec{B} \rightarrow -\vec{\mu} \cdot \vec{B},
  \]
  No other direction than spin $\Rightarrow \vec{d}$ parallel to $\vec{\mu}$ ($\vec{s}$).

- **Energy of electric dipole** $H = -\vec{d} \cdot \vec{E}$, includes term
  \[
  P \text{ or } T \quad \Rightarrow \quad \vec{s} \cdot \vec{E} \rightarrow -\vec{s} \cdot \vec{E},
  \]

- **Thus, EDMs violate both** $P$ and $T$ symmetry.
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  \text{Thus, EDMs violate both } P \text{ and } T \text{ symmetry.}
  \end{align*}$$

In rest frame of particle,

- **equation of motion for spin vector $\vec{S}$**:

  $$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}.$$  

Electric Dipole Moment Searches using Storage Rings

Frank Rathmann (JEDI collaboration)
Frozen-spin

Spin precession frequency of particle relative to direction of flight:

\[
\vec{\Omega} = \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} \\
= -\frac{q}{\gamma m} \left[ G \gamma \vec{B}_\perp + (1 + G) \vec{B}_\parallel - \left( G \gamma - \frac{\gamma}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right].
\] (5)

⇒ \(\vec{\Omega} = 0\) called frozen spin, because momentum and spin stay aligned.

- In the absence of magnetic fields \((B_\perp = B_\parallel = 0)\),

\[
\vec{\Omega} = 0, \text{ if } \left( G \gamma - \frac{\gamma}{\gamma^2 - 1} \right) = 0.
\] (6)

- Possible only for particles with \(G > 0\), such as proton \((G = 1.793)\) or electron \((G = 0.001)\).
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For protons, \((6)\) leads to magic momentum:

\[
G - \frac{1}{\gamma^2 - 1} = 0 \iff G = \frac{m^2}{p^2} \iff p = \frac{m}{\sqrt{G}} = 700.740 \text{ MeV } c^{-1}
\]
Protons at magic momentum in pure electric ring:

Recipe to measure EDM of proton:

1. Place polarized particles in a storage ring.
2. Align spin along direction of flight at magic momentum. \[ \Rightarrow \text{freeze horizontal spin precession.} \]
3. Search for time development of vertical polarization.

\[
\vec{\Omega} = 0 \quad \frac{d\vec{S}}{dt} = \vec{d} \times \vec{E}
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\[ \hat{\Omega} = 0 \]
\[ \frac{d\vec{S}}{dt} = \vec{d} \times \vec{E} \]

New method to measure EDMs of charged particles:

- Magic rings with spin frozen along momentum of particle.
- Polarization buildup \( P_y(t) \propto d \).
For any sign of $G$, in *combined* electric and magnetic machine:

- Generalized solution for magic momentum
  
  $$E_r = \frac{GB_y c \beta \gamma^2}{1 - G \beta^2 \gamma^2},$$

  where $E_r$ is radial, and $B_y$ vertical field.

- Some configurations for circular machine with fixed radius $r = 25$ m:

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Search for charged particle EDMs with frozen spins
Magic storage rings

For any sign of $G$, in *combined* electric and magnetic machine:

- Generalized solution for magic momentum
  \[ E_r = \frac{G B_y c \beta \gamma^2}{1 - G \beta^2 \gamma^2}, \quad (8) \]
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Offers possibility to determine

**EDMs of protons, deuterons, and helions in one and the same machine.**
Progress toward storage ring EDM experiments
Complementing the spin physics tool box

COoler SYnchrotron COSY

- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta $p = 0.3 - 3.7\ \text{GeV}/c$.
- Phase-space cooled internal and extracted beams.
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- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta \( p = 0.3 - 3.7 \text{ GeV/c} \).
- Phase-space cooled internal and extracted beams.

COSY formerly used as spin-physics machine for hadron physics:
- Provides an ideal starting point for srEDM related R&D.
- Will be used for a first direct measurement of deuteron EDM.
Progress toward storage ring EDM experiments

COSY Landscape

- WASA polarimeter
- EDDA polarimeter
- RF Wien filter equipped with Rogowski coils
- e-cooler
- Injection
**Principle of spin-coherence time measurement**

**Measurement procedure:**

1. Vertically polarized deuterons stored at $p \simeq 1$ GeV c$^{-1}$.
2. Polarization flipped into horizontal plane with RF solenoid ($\approx 200$ ms).
3. Beam extracted on Carbon target with ramped bump or by heating.
4. Horizontal (in-plane) polarization determined from $U - D$ asymmetry in polarimeter.
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Detector system: EDDA [14]

EDDA previously used to determine $\bar{p}p$ elastic polarization observables:

- Deuterons at $p = 1$ GeV $c^{-1}$, $\gamma = 1.13$, and $\nu_s = \gamma G \simeq -0.161$
- Spin-dependent differential cross section on unpolarized target:

$$N_{U,D} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\nu_s f_{\text{rev}} t), \text{ where } f_{\text{rev}} = 781 \text{ kHz.}$$

(9)
Progress toward storage ring EDM experiments

Precision determination of the spin tune \([15, \text{JEDI 2015 PRL}]\)

- Time-stamping events accurately,
  - allows us to monitor phase of measured asymmetry with (assumed) fixed spin tune \(\nu_s\) in a 100 s cycle:

\[
\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi} \frac{d\phi}{dn} \quad (10)
\]

\[
= \nu_s^{\text{fix}} + \Delta \nu_s(n)
\]

- Experimental technique allows for:
  - Spin tune \(\nu_s\) determined to \(\approx 10^{-8}\) in 2 s time interval.
  - In a 100 s cycle at \(t \approx 38\) s, interpolated spin tune amounts to

\[
|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}, \text{ i.e., } \frac{\Delta \nu_s}{\nu_s} \approx 10^{-10}.
\]

\Rightarrow \text{new precision tool to study systematic effects in a storage ring.}
Spin tune as a precision tool for accelerator physics

Walk of spin tune $\nu_s$ [15].

Applications of new technique:

- Study long term stability of an accelerator.
- Feedback system to stabilize phase of spin precession relative to phase of RF devices (so-called phase-lock).
- Study of machine imperfections (see N.N. Nikolaev on Tu at 17:20).
Optimization of spin-coherence time: JEDI 2014 PRL [16]

2012: Observed experimental decay of asymmetry

\[ \epsilon_{UD}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \quad (11) \]
Progress toward storage ring EDM experiments

Optimization of spin-coherence time: JEDI 2014 PRL [16]

\[ \tau_{\text{SCT}} \approx 20 \text{ s} \]

2012: Observed experimental decay of asymmetry

\[ \epsilon_{\text{UD}}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \quad (11) \]

\[ \tau_{\text{SCT}} \approx 400 \text{ s} \]

2013: Using sextupole magnets, higher order effects are corrected, and spin coherence substantially increased.
More optimizations of spin-coherence time: JEDI 2016 PRL [18]

Recent progress on $\tau_{\text{SCT}}$:

$\tau_{\text{SCT}} = (782 \pm 117) \text{ s}$

- Previously:
  $\tau_{\text{SCT}}(\text{VEPP}) \approx 0.5 \text{ s} [17]$  
  ($\approx 10^7$ spin revolutions).
More optimizations of spin-coherence time: JEDI 2016 PRL [18]

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$\tau_{SCT} = (782 \pm 117) \text{ s}$

- Previously:
  \[ \tau_{SCT}^{\text{(VEPP)}} \approx 0.5 \text{ s} \] [17]
  \( \approx 10^7 \text{ spin revolutions} \).

Spring 2015: Way beyond anybody’s expectation:

- With about $10^9$ stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of $\tau_{SCT}$ of crucial importance (1), since $\sigma_{\text{stat}} \propto \frac{1}{\tau_{SCT}}$. 
Progress toward storage ring EDM experiments

Phase locking spin precession in machine to device RF

At COSY, frozen spin is not possible

⇒ To achieve precision for EDM, phase-locking is next best thing to do.

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)

Major achievement: Error of phase-locking

$\sigma_{\phi} = 0.21$ rad

JEDI 2017 PRL[19]
Progress toward storage ring EDM experiments

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Major achievement: Error of phase-lock $\sigma_\phi = 2.1$ rad

JEDI 2017 PRL [19]

![Diagram of feedback system and data plots](image)
Phase locking spin precession in machine to device RF

At COSY, frozen spin is not possible
⇒ To achieve precision for EDM, phase-locking is next best thing to do.

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)

Major achievement: Error of phase-lock $\sigma_\phi = 0.21$ rad  

JEDI 2017 PRL [19].
More technical challenges of storage ring EDM experiments

Overview

Charged particle EDM searches require development of new class of high-precision machines with mainly electric fields for bending and focussing:

Main issues:

- Large electric field gradients $\sim 10$ to $20\,\text{MV/m}$.
- Spin coherence time $\tau_{\text{SCT}} \sim 1000\,\text{s}$ [18].
- Continuous polarimetry with relative errors $< 1\,\text{ppm}$ [20].
- Beam position monitoring with precision of $10\,\text{nm}$.
- High-precision spin tracking.
- Alignment of ring elements, ground motion, ring imperfections.
- Magnetic shielding.
- For deuteron EDM with frozen spin: precise reversal of magnetic fields for CW and CCW beams required.
E/B Deflector development using small-scale lab setup

Kirill Grigoriev (IKP, RWTH Aachen and FZJ)

- Polished stainless steel
  - 240 MV/m reached at distance of 0.05 mm with half-sphere facing flat surface.
  - 17 MV/m with 1 kV at 1 mm with two small half-spheres.
- Polished aluminum
  - 30 MV/m measured at distance of 0.1 mm using two small half-spheres.
- TiN coating
  - Smaller breakdown voltage.
  - Zero dark current.
E/B deflector development using real-scale lab setup

**Equipment:**
- Dipole magnet $B_{\text{max}} = 1.6$ T
- Mass = 64 t
- Gap height = 200 mm
- Protection foil between chamber wall and deflector

**Parameters:**
- Electrode length = 1020 mm
- Electrode height = 90 mm
- Electrode spacing = 20 to 80 mm
- Max. electric field = ±200 MV
- Material: Aluminum coated by TiN
E/B deflector development using real-scale lab setup

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**Next steps:**
Equipment ready for assembling. First test results expected before Christmas.
Beam position monitors for srEDM experiments

Compact new development based on segmented Rogowski coil

- Main advantage is short installation length of $\approx 1\,\text{cm}$ (along beam direction)

Conventional BPM
- Easy to manufacture
- length $= 20\,\text{cm}$
- resolution $\approx 10\,\mu\text{m}$

Rogowski BPM
- Excellent rf-signal response
- length $= 1\,\text{cm}$
- resolution $\approx 1.25\,\mu\text{m}$
Beam position monitors for srEDM experiments

Compact new development based on segmented Rogowski coil
- Main advantage is short installation length of ≈ 1 cm (along beam direction)

Conventional BPM
- Easy to manufacture
- Length = 20 cm
- Resolution ≈ 10 µm

Rogowski BPM
- Excellent rf-signal response
- Length = 1 cm
- Resolution ≈ 1.25 µm

- Two Rogowski coils already installed at entrance and exit of RF Wien filter
**dC polarimetry data base I**

**Motivation: Optimize polarimetry for ongoing JEDI activities:**
- Determine vector and tensor analyzing powers $A_y$, $A_{yy}$, and differential cross sections $d\sigma/d\Omega$ of $dC$ elastic scattering at
  - deuteron kinetic energies $T = 170 - 380$ MeV.

**Detector system: former WASA forward detector, modified**
- Targets: C and CH2
- Full azimuthal coverage, scattering angle range $\theta = 4^\circ - 17^\circ$. 

---

**Diagram**

- **Target position**
- **Window Counters**
  - Plastic scintillators
- **Proportional Chambers**
- **Range Hodoscopes**
  - Plastic scintillators
- **Trigger Hodoscope**
  - Plastic scintillator

Coordinates:
- $17^\circ$
- $4^\circ$
Preliminary results of elastic $dC$ analyzing powers

- Analysis of differential $dC$ cross sections in progress.
- JEDI just finished another similar data base run to provide $pC$ data base.
Preliminary results of elastic dC analyzing powers

- Analysis of differential dC cross sections in progress.
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see talk by Fabian Müller on We at 17:20
High-precision beam polarimeter with internal C target

Based on LYSO Scintillation Material

- Saint-Gobain Ceramics & Plastics: Lu$_{1.8}$Y$_{2}$SiO$_{5}$:Ce
- Compared to NaI, LYSO provides
  - high density (7.1 vs 3.67 g/cm$^3$),
  - very fast decay time (45 vs 250 ns).

After several runs with external beam:

- System ready for installation at COSY in 2019.
- Not yet ready: Ballistic diamond pellet target for homogeneous beam sampling.

see talk by Dito Shergelashvili on We at 17:00
Study of machine imperfections

JEDI developed a new method to investigate magnetic machine imperfections based on the highly accurate determination of the spin-tune Saleev PR AB 2017 [21].

Spin tune mapping

- Two cooler solenoids act as spin rotators ⇒ generate artificial imperfection fields.
- Measure spin tune shift vs spin kicks.

- Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}$ e cm.

see talk of N.N. Nikolaev on Tu at 17:20.
Prototype EDM storage ring

**Next step:**
- Build **demonstrator for charged-particle EDM**.
- Project prepared by a new CPEDM collaboration (CERN + JEDI).
  - Physics Beyond Collider process (CERN), and the
  - European Strategy for Particle Physics Update.
- Possible host sites: COSY or CERN

**Scope of the project**
- 30 MeV protons, all-electric operation, CW-CCW beams, 100 m circumference

- Storage time
- CW/CCW operation
- Spin coherence time
- Polarimetry
- Magnetic moment effects
- (pEDM measurement)
- Stochastic cooling

---

Electric Dipole Moment Searches using Storage Rings

Frank Rathmann (JEDI collaboration)
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Scope of the project

30 MeV protons, all-electric operation, CW-CCW beams, 100 m circumference

Subject discussed in detail by Sig Martin on We at 16:40

- Storage time
- Polarimetry
- Magnetic moment effects
- \( p\text{EDM} \) measurement
- Stochastic cooling
Highest EDM sensitivity shall be achieved with a new type of machine:

- An **electrostatic circular storage** ring, where
  - centripetal force produced primarily by electric fields.
  - $E$ field couples to EDM and provides required sensitivity ($< 10^{-28}$ e cm).
  - In this environment, magnetic fields mean evil (since $\mu$ is large).
Proof of principle experiment using COSY

**Precursor experiment**

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**Idea behind proof-of-principle experiment with novel RF Wien filter ($\vec{E} \times \vec{B}$):**

- In magnetic machine, particle spins (deuterons, protons) precess about stable spin axis ($\simeq$ direction of magnetic fields in dipole magnets).
- Use RF device operating on some harmonic of the spin-precession frequency:
  - $\Rightarrow$ Phase lock between spin precession and device RF.
  - $\Rightarrow$ Allows one to accumulate EDM effect as function of time in cycle ($\sim 1000 \text{ s}$).
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Goal of proof-of-principle experiment:

Show that conventional storage ring useable for first direct EDM measurement
RF Wien filter

A couple more aspects about the technique:

- RF Wien filter \((\vec{E} \times \vec{B})\) avoids coherent betatron oscillations in the beam:
  - Lorentz force \(\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0\).
  - EDM measurement mode: \(\vec{B} = (0, B_y, 0)\) and \(\vec{E} = (E_x, 0, 0)\).

![Diagram of RF Wien filter with stored d and Polarimeter (dp elastic)]
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Statistical sensitivity:

- in the range \(10^{-23}\) to \(10^{-24}\) e cm for \(d(\text{deuteron})\) possible.
- Systematic effects: Alignment of magnetic elements, magnet imperfections, imperfections of RF-Wien filter etc.
Model calculation of EDM buildup with RF Wien filter

Ideal COSY ring with deuterons at $p_d = 970$ MeV/c:

- $G = -0.143$, $\gamma = 1.126$, $f_s = |f_{\text{rev}}(\gamma G + K_{(=0)})| \approx 120.765$ kHz
- Electric RF field integral assumed $1000 \times \int E_{WF} \cdot d\ell \approx 2200$ kV (w/o ferrites)

Slim 2016 NIM [22].

EDM accumulates in $P_y(t) \propto d_{\text{EDM}}$ [21, 23, 24].
RF Wien filter

Overview

- RF Wien filter between PAX magnets.
RF Wien filter

Overview

- RF Wien filter between PAX magnets.
RF Wien filter

Overview

- RF Wien filter between PAX magnets. Upstream Rogowski coil;
RF Wien filter

Overview

- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W;
RF Wien filter

Overview

- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.
Design of RF Wien filter

Device developed at Jülich in cooperation with RWTH Aachen:

- Institute of High Frequency Technology, RWTH Aachen University:
  - Heberling, Hölscher, and PhD Student Jamal Slim, and ZEA-1 of Jülich.
- Waveguide provides $\vec{E} \times \vec{B}$ by design.
- Minimal $\vec{F}_L$ by careful electromagnetic design of all components [22].
Strength of EDM resonance

**EDM induced vertical polarization oscillations,**

- can generally be described by
  \[ p_y(t) = a \sin(\Omega_{py} t + \phi_{RF}) . \tag{12} \]

- Define **EDM resonance strength** \( \varepsilon_{\text{EDM}} \) as ratio of angular frequency \( \Omega_{py} \) relative to orbital angular frequency \( \Omega_{\text{rev}} \),
  \[ \varepsilon_{\text{EDM}} = \frac{\Omega_{py}}{\Omega_{\text{rev}}}, \tag{13} \]

**Alternatively,** \( \varepsilon_{\text{EDM}} \) is determined from the measured initial slopes \( \dot{p}_y(t)|_{t=0} \)

- through variation of \( \phi_{RF} \)
  \[ \varepsilon_{\text{EDM}} = \frac{\dot{p}_y(t)|_{t=0}}{a \cos \phi_{RF}} \cdot \frac{1}{\Omega_{\text{rev}}}. \tag{14} \]

- If \( |\vec{P}| = 1 \) \( \Rightarrow \dot{p}_y(t) = \dot{\alpha}(t) \)
First measurement of EDM-like buildup signals

Rate of out-of-plane rotation angle $\dot{\alpha}(t)|_{t=0}$ as function of Wien filter RF phase $\phi_{\text{RF}}$

- $B$ field of RF Wien filter normal to the ring plane.
- Wien filter operated at $f_{\text{WF}} = 871 \text{ kHz}$.
- Variations of $\phi_{\text{rot}}^{\text{WF}}$ and $\chi_{\text{rot}}^{\text{Sol1}}$ affect the pattern of observed initial slopes $\dot{\alpha}$.

\[ \dot{\alpha} \text{ for } \phi_{\text{rot}}^{\text{WF}} = -1^\circ, 0^\circ, +1^\circ \text{ and } \chi_{\text{rot}}^{\text{Sol1}} = 0. \]

\[ \dot{\alpha} \text{ for } \chi_{\text{rot}}^{\text{Sol1}} = -1, 0, +1^\circ \text{ and } \phi_{\text{rot}}^{\text{WF}} = 0. \]

Next steps:

- After commissioning, first EDM run scheduled for Nov-Dec/2018.
- see talk by Alexander Nass on Tu at 18:00
Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [25, 2011]

- Oscillating axion field is coupled with gluons and induces an oscillating EDM in hadronic particles.

Measurement principle:

- When oscillating EDM resonates with particle $g-2$ precession frequency in the storage ring, the EDM precession can be accumulated.
- Due to strong effective electric field ($\vec{v} \times \vec{B}$), sensitivity is improved significantly.

Coursey of Seongtae Park (IBS, Daejeon, ROK)
Limits for axion-gluon coupled to oscillating EDM

from Ref. [26]

Realization

- No new/additional equipment required!
- Can be done in magnetic storage ring (i.e., COSY)
- Proposal for test beam time accepted by CBAC.
- Experiment scheduled for I/2019.
Search for charged particle EDMs:

- New window to disentangle sources of $CP$ violation, and to possibly explain matter-antimatter asymmetry of the Universe.

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM.
- COSY remains a unique facility for such studies.
- First direct JEDI deuteron EDM measurement at COSY well underway.
  - Run scheduled for Nov-Dec.
  - Sensitivity $10^{-19} - 10^{-20}$ e cm.

- Strong interest of high energy community in storage ring searches for EDM of protons and light nuclei as part of physics program of the post-LHC era.
- Proposal for prototype all-electric 30 MeV EDM storage ring being prepared (possible hosts: CERN or COSY).
- Crossed $\vec{E} \times \vec{B}$ field prototype EDM storage ring might be an option before going to a TDR for the ultimate EDM machine.
JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

- ~ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...)
- http://collaborations.fz-juelich.de/ikp/jedi
Spares
Thomas-BMT equation with EDM and MDM

When particles orbit in an accelerator,

- Spin equation expressed in curvilinear laboratory reference frame.
- Solution called Thomas-BMT equation [27, 28] (historically ignoring EDM).
- Generalized form of Thomas-BMT equation, including EDMs [29]:

\[
\frac{d\vec{S}}{dt} = \vec{\Omega}_{MDM} \times \vec{S} + \vec{\Omega}_{EDM} \times \vec{S}, \quad \text{where}
\]

\[
\vec{\Omega}_{MDM} = -\frac{q}{m} \left[ \left( G + \frac{1}{\gamma} \right) \vec{B} - \frac{G \gamma}{\gamma + 1} (\vec{\beta} \cdot \vec{B}) \vec{\beta} - \left( G + \frac{1}{\gamma + 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right],
\]

(15)

\[
\vec{\Omega}_{EDM} = -\frac{q}{mc} \frac{\eta_{EDM}}{2} \left[ \vec{E} - \frac{\gamma}{\gamma + 1} (\vec{\beta} \cdot \vec{E}) \vec{\beta} + c \vec{\beta} \times \vec{B} \right].
\]

- $\vec{S}$ given in particle rest frame, $\vec{E}$ and $\vec{B}$ in laboratory system.
- MDM and EDM defined via dimensionless quantities $g$ and $\eta_{EDM}$:

\[
\vec{\mu} = g \frac{q}{2m} \vec{S}, \quad \text{and} \quad \vec{d} = \eta_{EDM} \frac{q}{2mc} \vec{S}, \quad \text{with} \quad G = \frac{g - 2}{2}.
\]

(16)
Another way to look at $\tilde{\Omega}_{\text{MDM}}$:

- Decomposing precession frequencies: $\tilde{\Omega}_{B\parallel}$, $\tilde{\Omega}_{B\perp}$, and $\tilde{\Omega}_{E\perp}$ leads to

$$
\tilde{\Omega}_{\text{MDM}} = \tilde{\Omega}_{B\parallel} + \tilde{\Omega}_{B\perp} + \tilde{\Omega}_{E\perp} = -\frac{q}{\gamma m} \left[ (1 + G\gamma)\vec{B}_{\perp} + (1 + G)\vec{B}_{\parallel} - \left( G\gamma + \frac{\gamma}{\gamma + 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]
$$

- Including an electric field, cyclotron frequency becomes

$$
\tilde{\Omega}_{\text{cyc}} = -\frac{q}{\gamma m} \left( \vec{B}_{\perp} - \frac{\vec{\beta} \times \vec{E}}{\beta^2 c} \right), \quad \text{and}
$$

- Particle momentum vector $\vec{p}$ rotates with

$$
\frac{d\vec{p}}{dt} = \tilde{\Omega}_{\text{cyc}} \times \vec{p}.
$$
Expectation for $d = 10^{-20}$ e cm in ideal COSY ring

(a) $\varepsilon^{\text{EDM}}$ for $d = 10^{-20}$ e cm.

(b) Contour plot of (a).

Resonance strengths $\varepsilon^{\text{EDM}}$ from Eq. (13) ($\approx 175$ random-points)

- $\phi^{\text{WF}}_{\text{rot}} = [-1^\circ, \ldots, +1^\circ]$,
- $\chi^{\text{Sol} 1}_{\text{rot}} = [-1^\circ, \ldots, +1^\circ]$ (100 keV cooler), and
- $\chi^{\text{Sol} 2}_{\text{rot}} = 0$ (2 MeV cooler).

- Each point from calculation with $n_{\text{turns}} = 50\,000$ and $n_{\text{points}} = 200$. 
Expectation for $d = 10^{-18}$ e cm in ideal COSY ring

(c) $\varepsilon^\text{EDM}$ for $d = 10^{-18}$ e cm.

(d) Contour plot of (c).

Resonance strengths $\varepsilon^\text{EDM}$ from Eq. (13) ($\approx$ 175 random-points)

- $\phi_{\text{rot}}^{WF} = [-0.1^\circ, \ldots, +0.1^\circ]$, 
- $\chi_{\text{rot}}^{\text{Sol 1}} = [-0.1^\circ, \ldots, +0.1^\circ]$ (100 keV cooler), and 
- $\chi_{\text{rot}}^{\text{Sol 2}} = 0$ (2 MeV cooler).

Each point from calculation with $n_{\text{turns}} = 200\,000$ and $n_{\text{points}} = 100$. 
References I


References II

References III


