

Electric Dipole Moment Measurements at Storage Rings

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RWTH Aachen & FZ Jülich
on behalf of the JEDI collaboration



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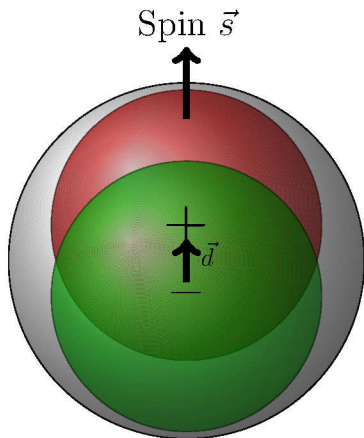
"Discrete symmetries in particle, nuclear and atomic physics
and implications for our universe".

Outline

- Motivation for Electric Dipole Moment (EDM) Measurements
- **Charged** particle EDM measurements achievements, activities, plans

Motivation for Electric Dipole Moment (EDM) Measurements

Electric Dipole Moments (EDM)



- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal \mathcal{T} and parity \mathcal{P} symmetry
- has nothing to do with electric dipole moments observed in some molecules (e.g. water molecule)



2016

PARTICLE PHYSICS BOOKLET

Extracted from the Review of Particle Physics
C. Patrignani et al. (Particle Data Group),
Chin. Phys. C, 40, 100001 (2016).
See <http://pdg.lbl.gov/> for Particle Listings,
complete reviews and pdginfo.

Available from PDG at LBNL and CERN



$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.00727646688 \pm 0.00000000009$ u

Mass $m = 938.272081 \pm 0.000006$ MeV [a]

$$|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}, \text{ CL} = 90\% [b]$$

$$|\frac{q_{\bar{p}}}{m_{\bar{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$$

$$|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}, \text{ CL} = 90\% [b]$$

$$|q_p + q_e|/e < 1 \times 10^{-21} [c]$$

Magnetic moment $\mu = 2.792847351 \pm 0.000000009 \mu_N$

$$(\mu_p + \mu_{\bar{p}}) / \mu_p = (0 \pm 5) \times 10^{-6}$$

Electric dipole moment $d < 0.54 \times 10^{-23}$ e cm

$$\text{Electric polarizability } \alpha = (11.2 \pm 0.4) \times 10^{-4} \text{ fm}^3$$

$$\text{Magnetic polarizability } \beta = (2.5 \pm 0.4) \times 10^{-4} \text{ fm}^3 \quad (S = 1.2)$$

Charge radius, μp Lamb shift $= 0.84087 \pm 0.00039$ fm [d]

Charge radius, $e p$ CODATA value $= 0.8751 \pm 0.0061$ fm [d]

Magnetic radius $= 0.78 \pm 0.04$ fm [e]

Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \rightarrow$ invisible mode)

Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

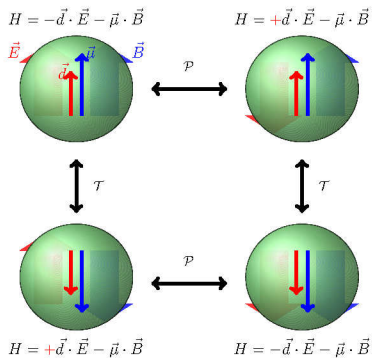
\mathcal{T} and \mathcal{P} violation of EDM

\vec{d} : EDM

$\vec{\mu}$: magnetic moment

both \parallel to spin

	$H = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$
\mathcal{T} :	$H = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$
\mathcal{P} :	$H = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$

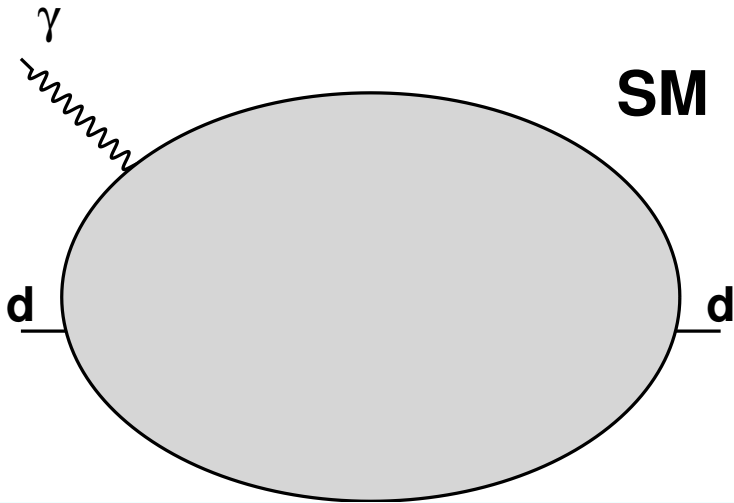


\Rightarrow EDM measurement tests violation of fundamental symmetries \mathcal{P} and \mathcal{T} ($\overset{CP\mathcal{T}}{=}\mathcal{CP}$)

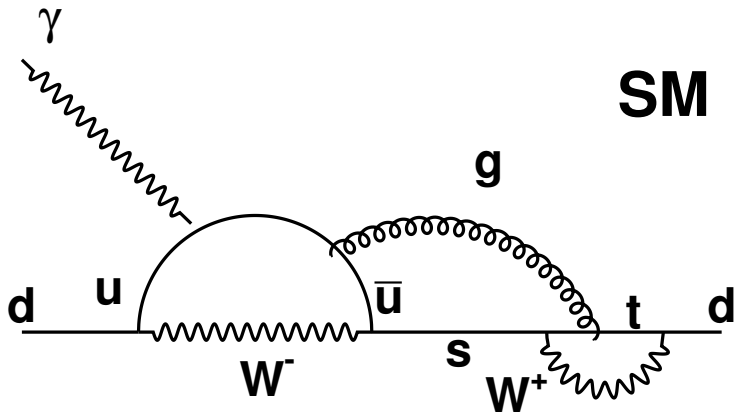
\mathcal{CP} – Violation & connection to EDMs

Standard Model	
Weak interaction CKM matrix	→ unobservably small EDMs
Strong interaction θ_{QCD}	→ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	→ accessible by EDM measurements

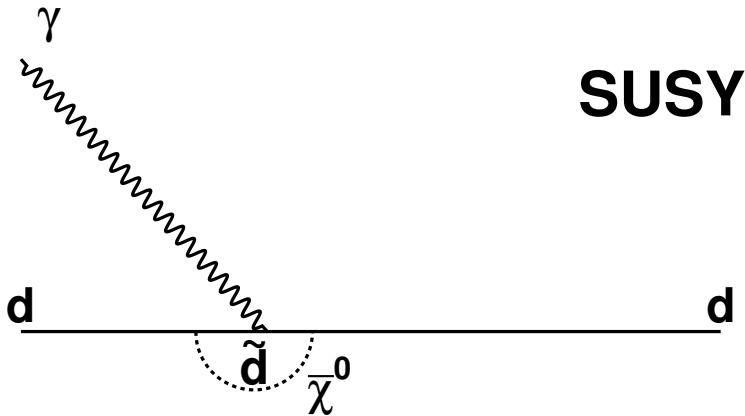
EDM in SM and SUSY



EDM in SM and SUSY



EDM in SM and SUSY



... implications for our universe

Excess of matter in the universe:

	observed	SCM* prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

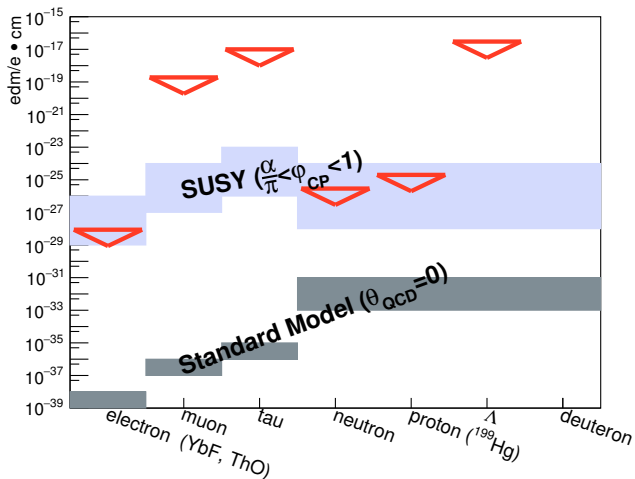
Sakharov (1967): \mathcal{CP} violation needed for baryogenesis

⇒ New \mathcal{CP} violating sources beyond SM needed to explain this discrepancy

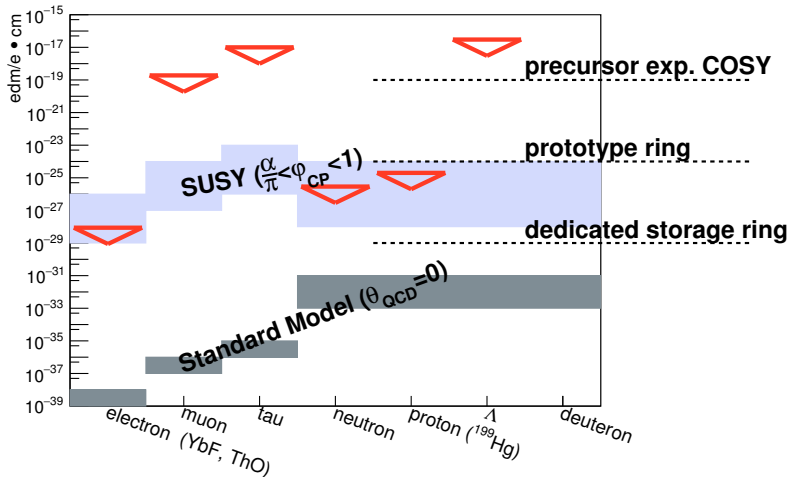
They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

EDM: Current Upper Limits



EDM: Current Upper Limits



FZ Jülich: EDMs of **charged** hadrons: $p, d, {}^3\text{He}$

Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
 - longer life time,
 - more stored protons/deuterons

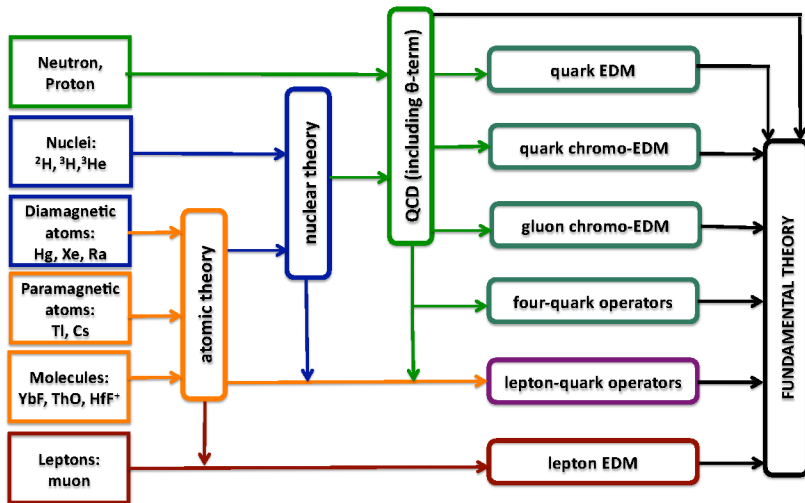
- complementary to neutron EDM:

$d_d, d_p, d_n \Rightarrow$ access to θ_{QCD}

(A. Wirzba, J. Bsaisou, A. Nogga, Int.J.Mod.Phys. E26 (2017)
no.01n02, 1740031)

EDM of one particle alone not sufficient to identify \mathcal{CP} -violating source

Sources of \mathcal{CP} Violation



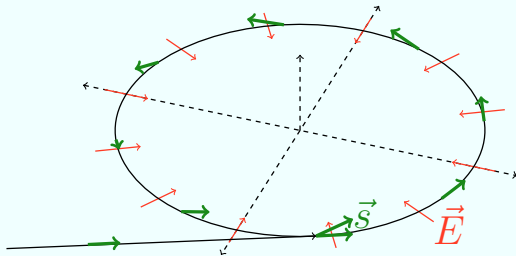
Charged particle EDM
measurements
achievements, activities,
plans

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, ...):

Interaction of \vec{d} with electric field \vec{E}

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



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

In general:

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

build-up of vertical polarisation $s_{\perp} \propto |d|$
(can be measured via elastic scattering on carbon)

Spin Precession: Thomas-BMT Equation

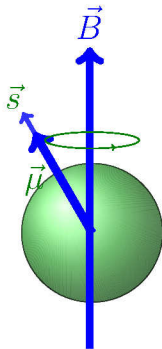
$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m} \left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2} (\vec{E} + \vec{v} \times \vec{B}) \right] \times \vec{s}$$

$$\vec{d} = \eta \frac{q}{2m} \vec{s}, \quad \vec{\mu} = 2(G + 1) \frac{q}{2m} \vec{s}$$

BMT: Bargmann, Michel, Telegdi

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1.) pure electric ring	no \vec{B} field needed, CW/CCW beams simultaneously	works only for particles with $G > 0$ (e.g. p)
2.) combined ring	works for $p, d, {}^3\text{He}, \dots$	both \vec{E} and \vec{B} required
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G , i.e. no frozen spin

ideal: suppress precession due to magnetic dipole moment
(**frozen spin**)

$$\vec{d} = \eta \frac{q}{2m} \vec{s}, \quad \vec{\mu} = 2(G + 1) \frac{q}{2m} \vec{s}$$

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Different Options

- First measurement with existing magnetic ring COSY at FZ Jülich



Jülich **E**lectric **D**ipole Moment **I**nvestigations

- Plans for a prototype/dedicated ring:
CPEDM collaboration (CERN, JEDI, Korea, ...)



Experimental Requirements

- high precision storage ring → **systematics**
(alignment, stability, field homogeneity)
- high intensity beams ($N = 4 \cdot 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- long spin coherence time ($\tau = 1000$ s),
- large electric fields ($E = 10$ MV/m)
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

$$\sigma_{\text{stat}} \approx \frac{\hbar}{\sqrt{N} f \tau P A E} \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29} \text{ e}\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

Test Measurements at COSY



COoler SYnchrotron COSY at Forschungszentrum provides (polarized) protons and deuterons with $p = 0.3 - 3.7 \text{ GeV}/c$
⇒ **Ideal starting point for charged hadron EDM searches**

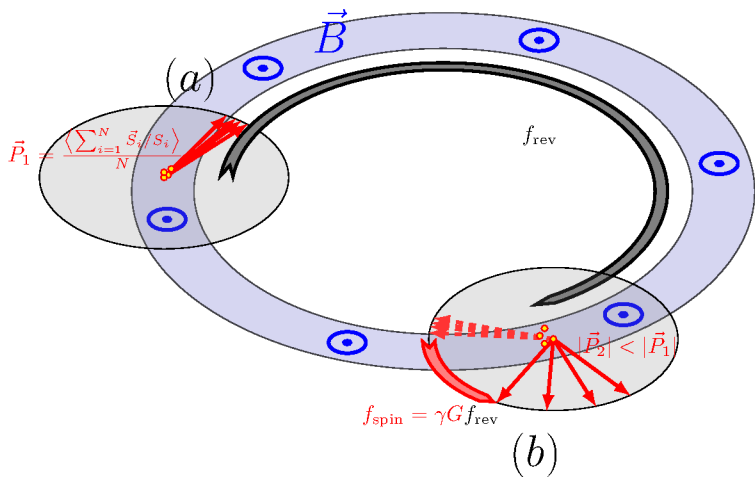
Recent achievements

- ① **Spin coherence time:** $\tau > 1000$ s
(PRL 117, 054801 (2016))
- ② **Spin tune:** $\overline{\nu}_s = -0.16097 \dots \pm 10^{-10}$ in 100 s
(PRL 115, 094801 (2015))
- ③ **Spin feedback:** polarisation vector kept within 12 degrees
(PRL 119 (2017) no.1, 014801)

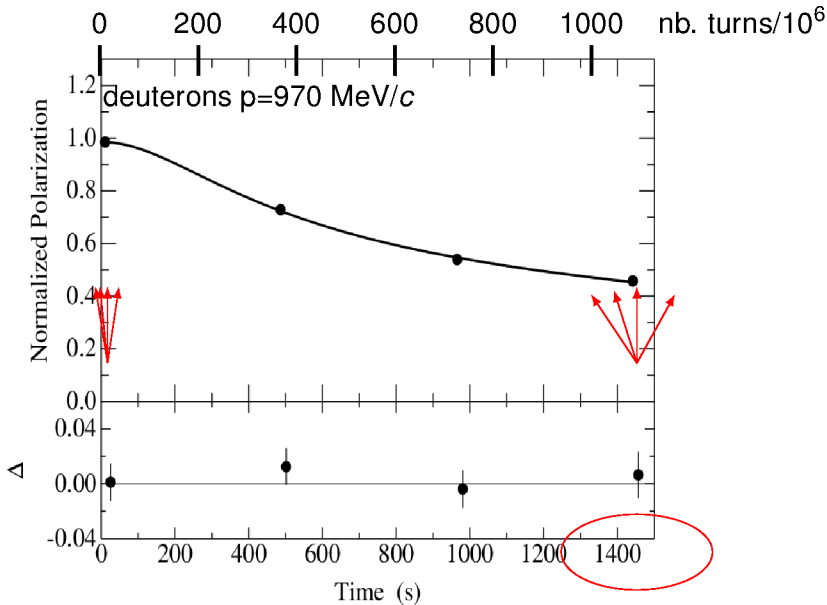
(all data shown were taken with deuterons, with $p \approx 1$ GeV/c)

- ① mandatory to reach statistical sensitivity
- ② & ③ shows that we can measure and manipulate polarisation vector with high accuracy

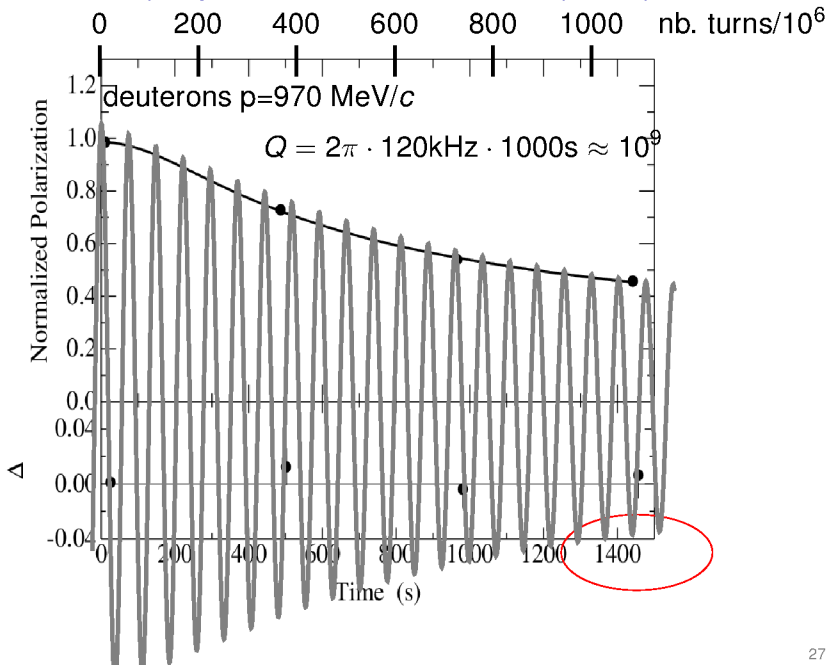
Spin Precession



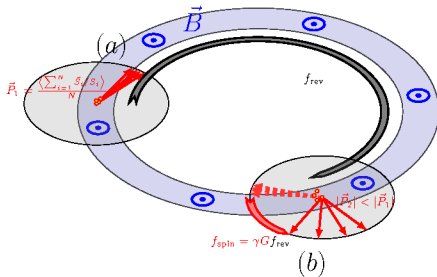
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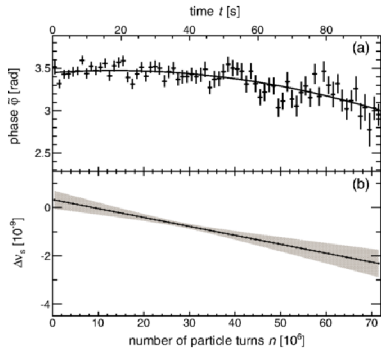


2.) Spin Tune ν_s



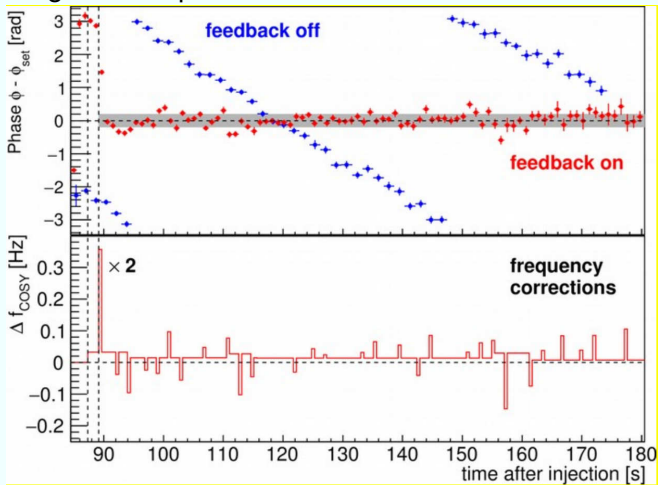
$$\sigma(\nu_s = \gamma G) \approx 10^{-10} \text{ in } 100 \text{ s}$$

$$\sigma(\nu_s = \gamma G) \approx 10^{-8} \text{ in } 2 \text{ s}$$



3.) Polarisation feedback

Controlling 120kHz precession

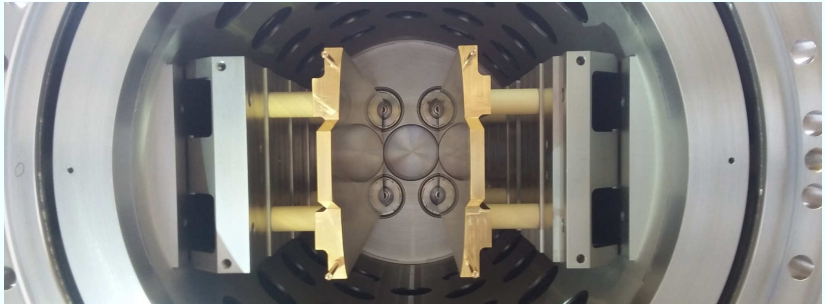
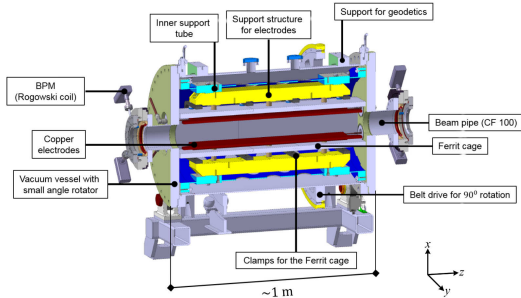


Towards a first deuteron EDM measurement

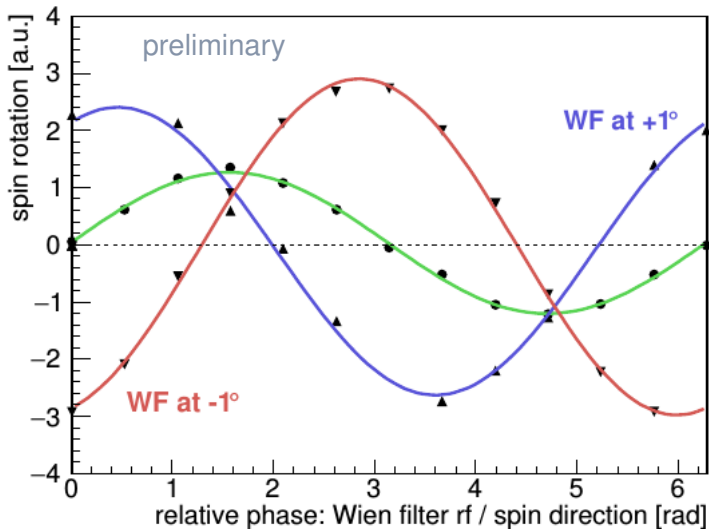
- Spin Manipulation and Measurement ✓
- In magnetic storage ring EDM just causes oscillation with tiny oscillation in vertical plane
- **Wien-filter** operating at spin precession frequency leads to vertical polarisation build-up due to EDM (and unfortunately also due to misalignments of storage ring elements)

⇒ EDM measurement possible at magnetic storage ring

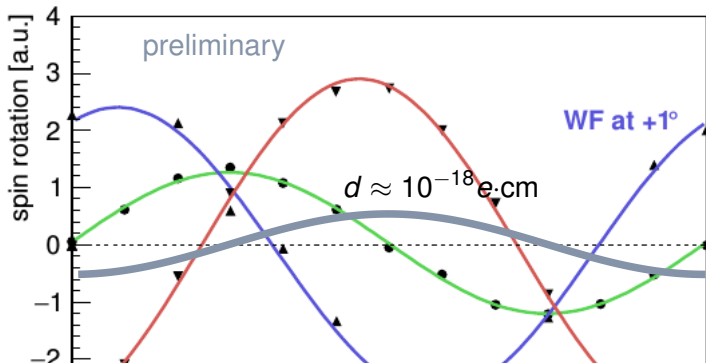
Wien filter



Results from Nov. 2017 Beam Time



Results from Nov. 2017 Beam Time



- ≈ 1 day of data taking \Rightarrow stat. error $\approx 10^{-19}$ ecm not a problem
- simulations are ongoing to understand effects of misalignments (here mimicked by rotation of WF)

Activities

- required for first EDM measurement:
 - maximize spin coherence time (SCT)
 - precise measurement of spin precession (spin tune)
 - polarisation feed back
 - RF- Wien filter

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 - spin tracking simulation (measured polarisation \rightarrow EDM)
 - theory (pEDM, dEDM, eEDM, $\dots \rightarrow$ underlying theory)

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- Design of dedicated storage ring:
 - accelerator lattice
 - polarimeter development
 - development of electro static deflectors

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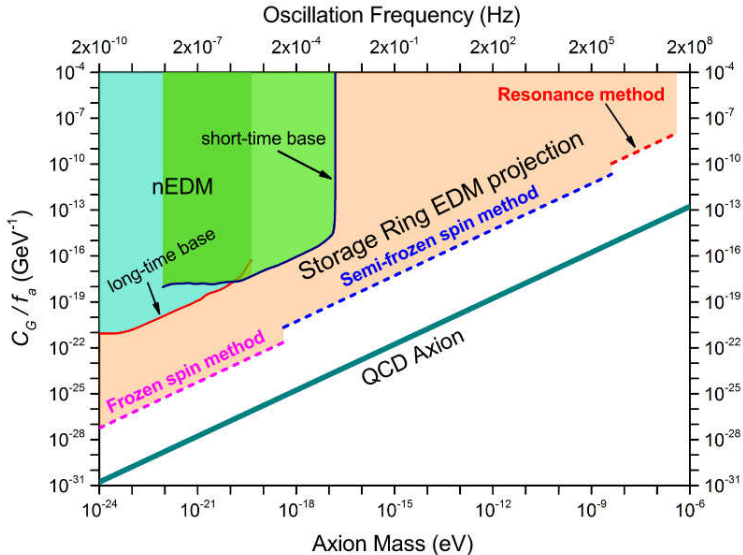
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 - accelerator lattice
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 - development of electro static deflectors
- other observables:
 - axion searches
(axions may lead to oscillating EDM)

Summary

- EDMs are unique probe to search for new CP-violating interactions
- **charged** particle EDMs can be measured in storage rings
- step wise approach: precursor at COSY \rightarrow prototype ring (100 m) \rightarrow dedicated ring (400 m)

Spare

Axion Search



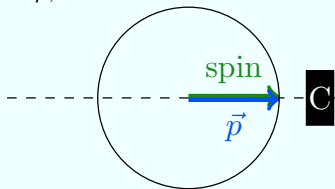
Asymmetry Measurements

- Detector signal $N^{up,dn} \propto (1 \pm P A \sin(\gamma G \omega_{rev} t))$

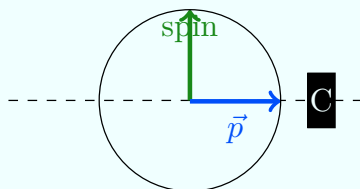
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P A \sin(\gamma G \omega_{rev} t)$$

A : analyzing power, P : polarization

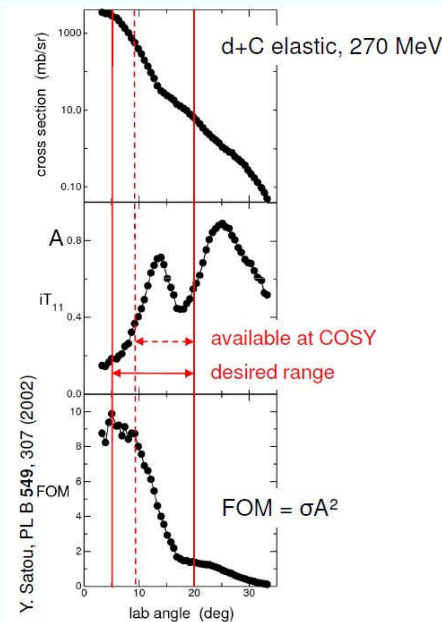
$$A_{up,dn} = 0$$



$$A_{up,dn} = PA$$



Polarimetry



Cross Section &
Analyzing Power
for deuterons

$$N_{up,dn} \propto (1 \pm P A \sin(\nu_s \omega_{rev} t))$$

$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P A \sin(\nu_s \omega_{rev} t)$$

A : analyzing power
 P : beam polarization