Measurement of the deuteron static and oscillating electric dipole moment at the COoler SYnchrotron COSY

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on behalf of the JEDI collaboration

SSP2025, Nara, Japan, Sep 2025

COoler SYnchrotron COSY

- storage ring at Forschungszentrum Jülich in Germany
- polarized proton & deuteron beam up to a momentum of 3.7 GeV/c
- JEDI (Jülich Electric Dipole moment Investigations) collaboration
- stopped operation in 2023

SSP 2018 Aachen, Germany → SSP 2025 Nara

Aachen Cathedral

Todai-ji temple

both conference venues in walking distance from UNESCO world heritage site, built at the same time

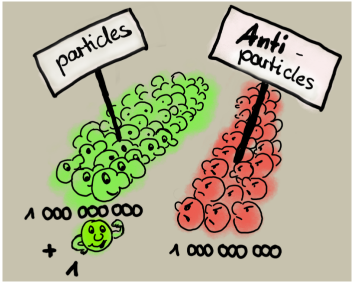
construction started in: 796 738

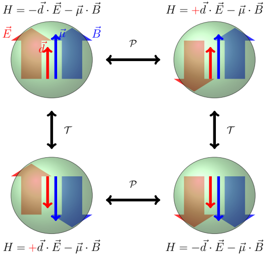
both cities where the capital and seat of the emporor at this time

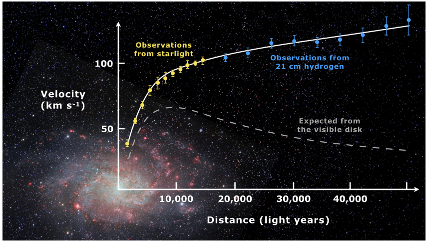
Motivation

Standard Model of Particle Physics successful but . . .

- Fails to explain matter-antimatter asymmetry in the universe
- Why is CP-violation in the strong sector not present (although allowed)?
- What does Dark Matter consists of?







source:M. De Leo, Wikipedia

Outline

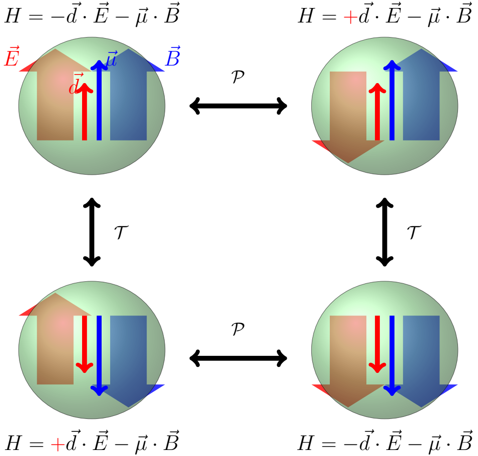
- **Introduction:**
  Electric Dipole Moments and connection to axions/ALPs
- **Experimental Methods for charged particles**
  Observing and controlling spin precession
- **Experiments & Results:**
  on permanent & oscillating electric dipole moments

Introduction

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

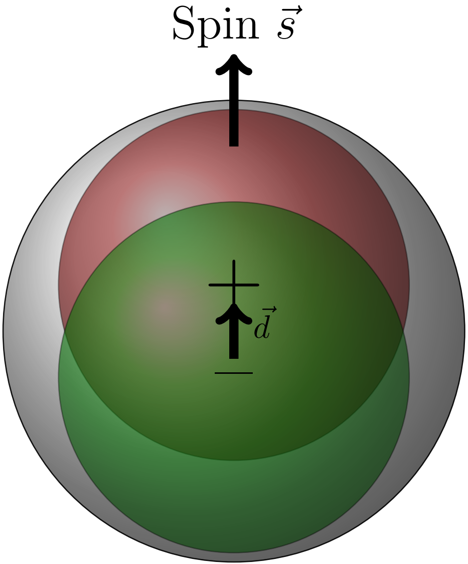
$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment (MDM)
both || to spin $\vec{s}$

	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 $\mathcal{T}$($\overset{\mathcal{CPT}}{=}$ $\mathcal{CP}$)

Electric Dipole Moments (EDM)



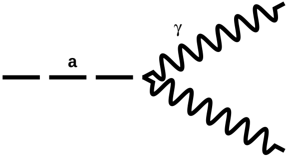
- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \stackrel{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to “matter-antimatter” asymmetry
- axion field leads to oscillating EDM
  $$d = d_{DC} + d_{AC} \cos(\omega_a t + \varphi_a)$$
  $$m_a c^2 = \hbar\omega_a$$

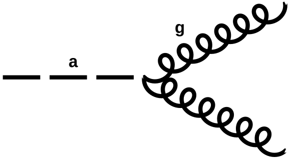
Axions/Axion Like Particles (ALPs)

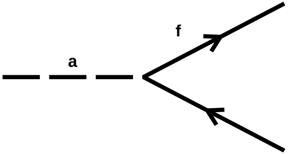
- hypothetical pseudo-scalar elementary particle postulated by Peccei,Quinn,Wilczek,Weinberg to resolve the strong CP problem
- axion are also Dark Matter candidates
- axion like particles (ALP): similar properties as axions, (but ALPs don't solve the strong QCD problem)
- huge experimental effort to search for axion/ALPs (haloscopes, helioscopes, light shining through the wall, mainly coupling to photons)
- in storage rings with polarized beams axion-gluon/nucleon coupling can be studied

Axion Coupling

$$\mathcal{L} : -\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad -\frac{\alpha_s}{8\pi}\frac{C_G}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} \qquad -\frac{1}{2}\frac{C_N}{f_a}\,\partial_\mu a\, \bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f$$







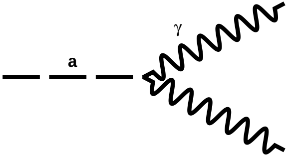
oscillating
Electric Dipole Moment (oEDM)

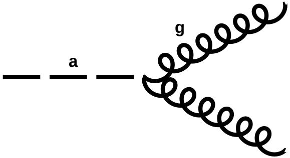
axion wind term

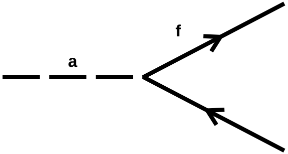
For low axion masses, if axions saturate dark matter they can be described by classical field: $a(t) = a_0 \cos(\omega_a t + \varphi_a)\,, \quad m_a c^2 = \hbar\omega_a\,, \quad$ Coupling $\propto \frac{1}{f_a} \propto m_a$ [1]

Axion Coupling

$$\mathcal{L}: -\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \quad -\frac{\alpha_s}{8\pi}\frac{C_G}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} \quad -\frac{1}{2}\frac{C_N}{f_a}\partial_\mu a\, \bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f$$







oscillating
Electric Dipole Moment (oEDM)

axion wind term

studied by many experiments
[1]

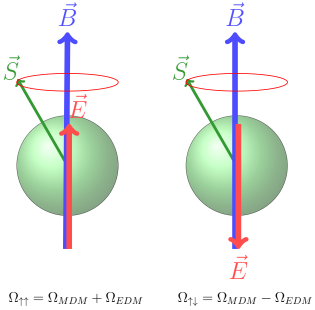
accessible in storage ring experiments with spin polarized beams

Experimental Methods

Experimental Method

Observe Spin Precession in electric and magnetic fields:

$$\vec{\Omega} = \frac{-d\vec{E} - \mu\vec{B}}{|\vec{s}|}, \qquad \dot{\vec{s}} = \vec{\Omega} \times \vec{s}$$



Order of magnitude:

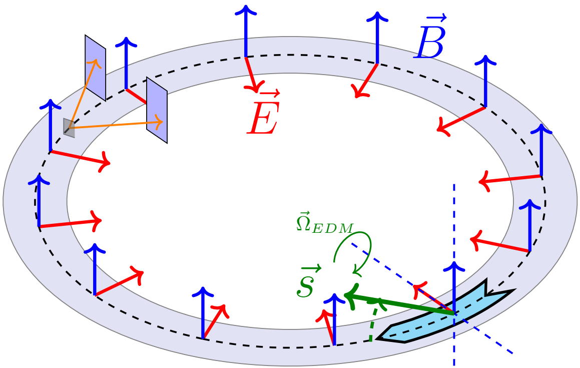
Neutron in earth B-field: $\Omega_{\mathrm{MDM}} \approx 9000\,\mathrm{s}^{-1}$

$d_n = 1 \times 10^{-26}\,\mathrm{e \cdot cm}$

in electric field $E = 10^7\,\mathrm{V/m}$: $\Omega_{\mathrm{EDM}} \approx 3 \times 10^{-6}\,\mathrm{s}^{-1}$

Even more complicated for charged particles:

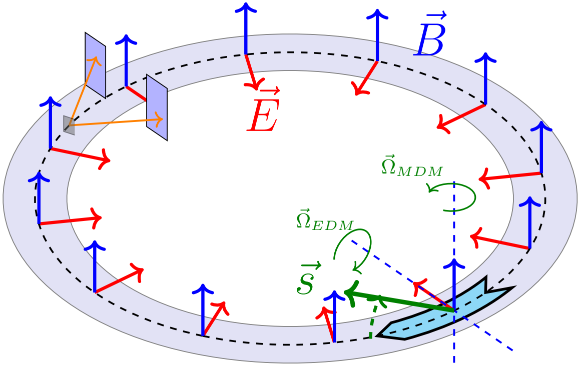
Experimental Method for charged particle: Storage Ring



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \underbrace{d(\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}} \times \vec{s}$$

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{\mathrm{horz}} || \vec{p}$ (**frozen spin**)

Experimental Method for charged particle: Storage Ring



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto d\underbrace{(\vec{E} + \vec{v} \times \vec{B}) \times \vec{s}}_{= \vec{\Omega}_{\mathrm{EDM}}}$$

In general:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}) \times \vec{s}$$

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{\mathrm{horz}} || \vec{p}$ (**frozen spin**)

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{= \vec{\Omega}_{\mathrm{MDM}}} + \underbrace{\frac{\eta}{2c}(\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}}\right] \times \vec{s}$$

electric dipole moment (EDM): $\vec{d} = \eta \frac{q\hbar}{2mc}\vec{s}$,

magnetic dipole moment (MDM): $\vec{\mu} = 2(G + 1)\frac{q\hbar}{2m}\vec{s}$

Note: $\eta = 2 \cdot 10^{-15}$ for $d = 10^{-29}$ecm, $G \approx 1.79$ (-0.14) for protons (deuterons)

Spin Precession: Thomas-BMT Equation

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

$\underbrace{}$ $\vec{\Omega}_{\mathrm{MDM}} = 0\,,$ **frozen spin** $\qquad \underbrace{}$ $= \vec{\Omega}_{\mathrm{EDM}}$

frozen spin achievable with pure electric field if $G = \dfrac{1}{\gamma^2 - 1}$,

works only for $G > 0$, e.g. proton

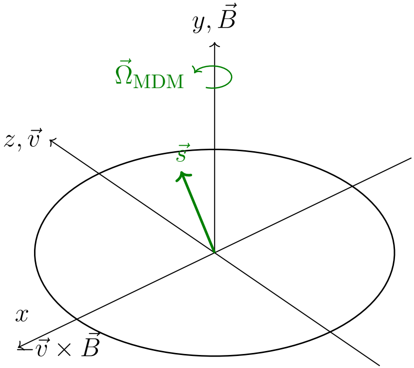
or with special combination of E, B fields and γ, i.e. momentum

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\Bigg[\underbrace{G\vec{B}}_{=\vec{\Omega}_{\mathrm{MDM}}} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \underbrace{\frac{\eta}{2c}(\vec{E} + \vec{v} \times \vec{B})}_{=\vec{\Omega}_{\mathrm{EDM}}}\Bigg] \times \vec{s}$$

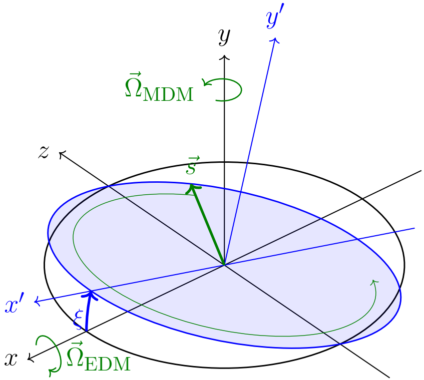
In COSY, only *B*-field available:
⇒ spin precession due to MDM cannot be (completely) suppressed
⇒ no macroscopic build-up of vertical polarisation component

Spin Precession

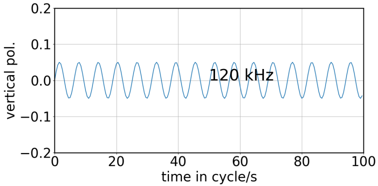


- Without EDM spin rotates around vertical *y*-axis

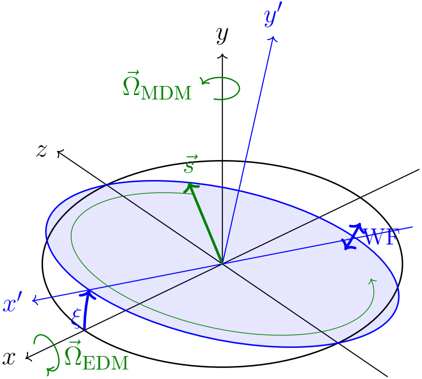
Spin Precession



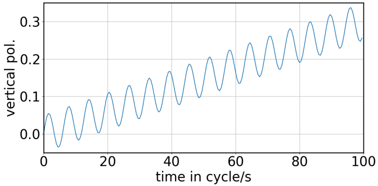
- Without EDM spin rotates around vertical y-axis
- EDM causes a tilt of invaraint spin axis in radial x-direction of $\xi \approx \frac{\eta\beta}{2G}$
- This resluts in an oscillation of the vertical polarisation component



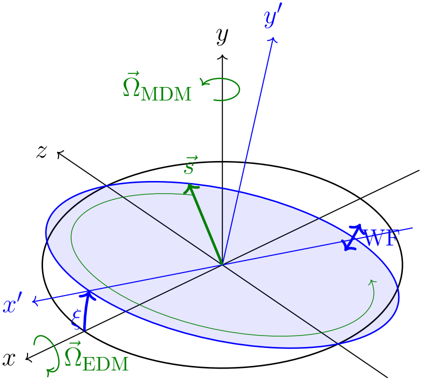
Spin Precession



- Without EDM spin rotates around vertical y-axis
- EDM causes a tilt of invaraint spin axis in radial x-direction of $\xi \approx \frac{\eta\beta}{2G}$
- This resluts in an oscillation of the vertical polarisation component
- With an resonant spin kick (provided by a rf Wien filter) a macroscopic bulid-up of a vertical polarisation can be achieved



Spin Precession



- Without EDM spin rotates around vertical *y*-axis
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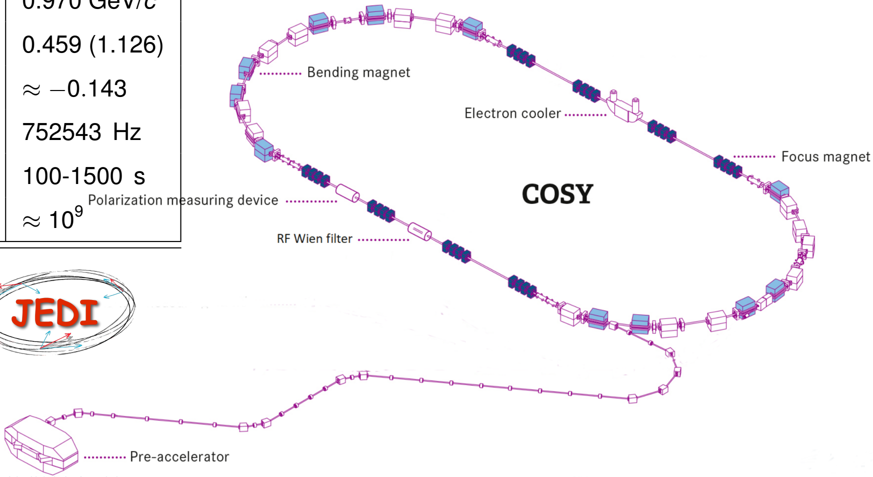
- This resluts in an oscillation of the vertical polarisation component
- With an resonant spin kick (provided by a rf Wien filter) a macroscopic bulid-up of a vertical polarisation can be achieved
- Misalignments, ... lead to additional tilt in precession plane in *x* and *z*-direction

Experiments & Results

Experiments at COSY

COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency f_{rev}	752543 Hz
cycle length	100-1500 s
nb. of stored particles/cycle	$\approx 10^9$



JEDI collaboration, JEDI

COler SYnchrotron COSY

Tools developed to manipulate and measure beam polarization:

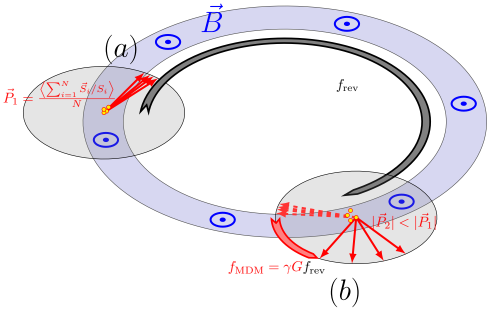
- reaching > 1000 s spin coherence time
- measure 120 kHz spin tune precession in horizontal plane to 10^{-10} in 100 s
- development of polarization feed back system
- radio frequency Wien filter
- (single bunch spin manipulation [3], Beam Position Monitors (BPMs) [4], deflector [5], polarimeter [6], ...)

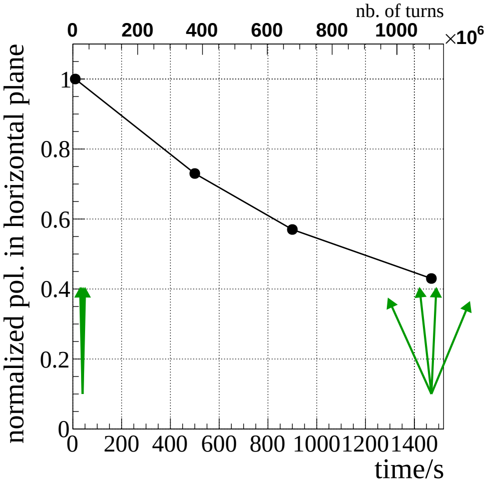
Results on:

- permanent deuteron EDM
- oscillating deuteron EDM

Long Spin Coherence Time (SCT)

Long Spin Coherence time > 1000 s reached





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Long Spin Coherence Time (SCT)

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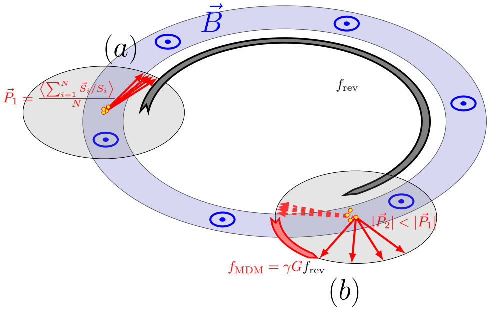
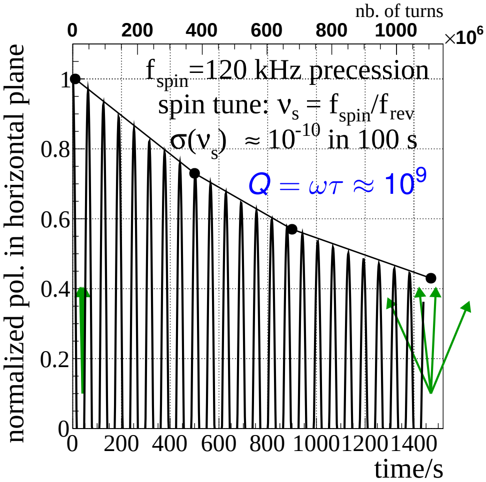
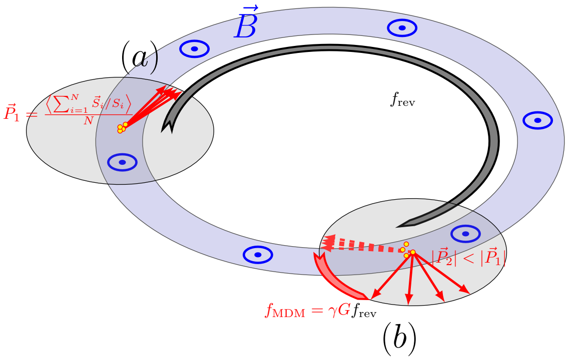
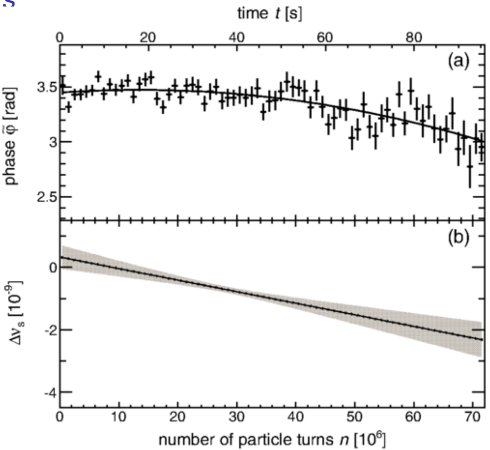








Spin tune $\nu_s = \frac{\Omega_{MDM}}{\Omega_{rev}} \approx \gamma G$

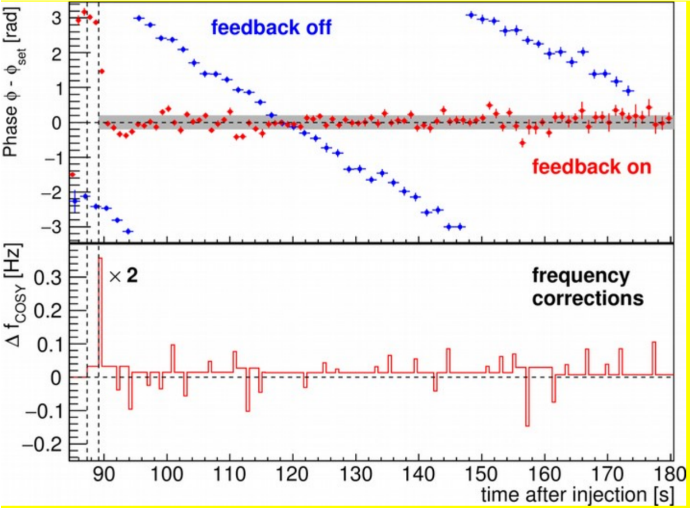
$\sigma(\nu_s = \gamma G) \approx 10^{-10}$ in 100 s

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

[8]

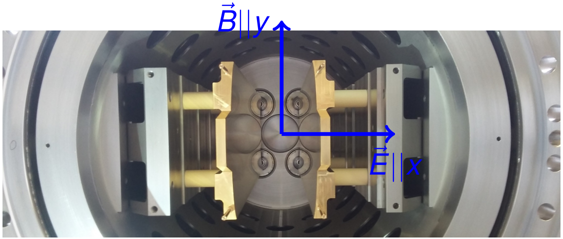
Polarisation feedback

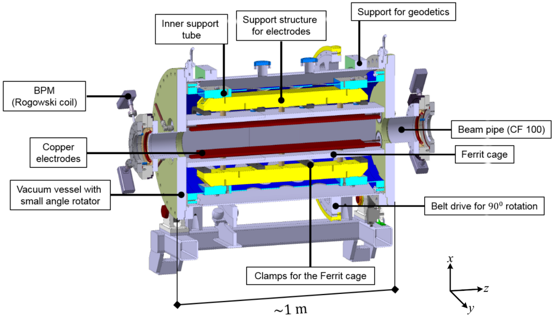
Controlling 120kHz precession, Φ: phase between spin precession and rf-device



[9]

Radio frequency Wien filter





- field: $2.7 \cdot 10^{-2}$Tmm for 1kW input power
- frequency range: 100 kHz-2MHz
- $\vec{F}_L = e(\vec{E} + \vec{v} \times \vec{B}) = 0$ $\Rightarrow$ no incluence on orbit, but on spin

[10]

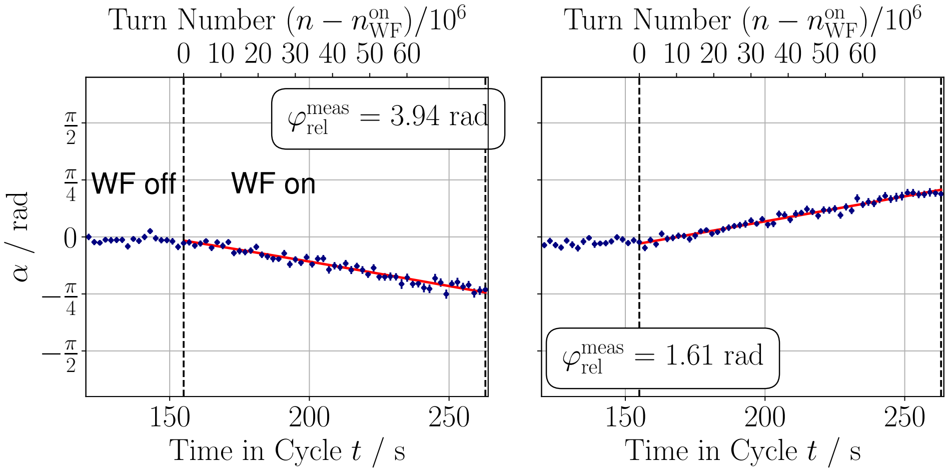
Towards deuteron EDM measurement

Observable: Build-up of vertical polarisation

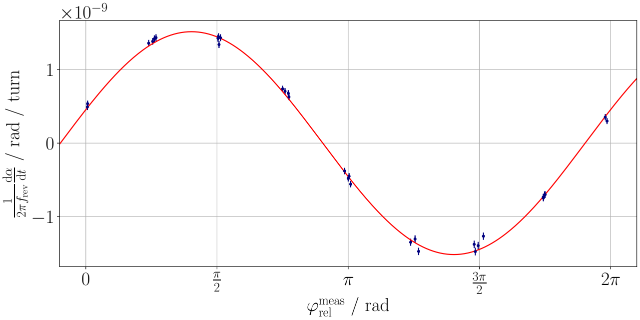
$$\frac{d\alpha}{dt} = \frac{1}{2}\left(\frac{\eta\beta}{2G} + \xi_{syst}\right)\Psi_0 f_{rev}\cos(\varphi_{\mathrm{rel}})$$

- $\alpha = \frac{P_V}{P_H}$, ratio of vertical to horizontal polarisation
- Ψ_0: amplitude of Wien filter spin kick per turn
- φ_{rel} = phase between WF and spin precession
- $\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s}$
- ξ_{syst} : due to misalignments, field imperfections, ...

Polarisation Build-up



Slopes as a function of φ_{rel}



- Measured amplitude would correspond to EDM of d_{deuteron} of $1.6 \approx 10^{-17} e\text{cm}$ or to e.g. magnet misalignments of $\mathcal{O}(\text{mrad})$
- Result dominated by systematics. $\Rightarrow$ EDM limit 95% CL for deuteron of $\approx 3 \cdot 10^{-17} e\text{cm}$ (preliminary)

Comparison to other direct EDM measurements

Only other direct measurment of charged particle exists for muon

	d	G
BNL muon 95% CL	1.9×10^{-19} cm	$\approx \frac{\alpha}{2\pi} = 0.001$
JEDI deuteron EDM 95% CL	$\approx 3 \times 10^{-17}$ cm	-0.14

Note, sensitivity $\propto \frac{d}{G}$

Deuteron result obtained with conventional storage ring, not designed for precision measurments
$\Rightarrow$ Dedicated storage ring (electric bending elements, ↺ & ↻ beams) needed

[11]

Axion Searches

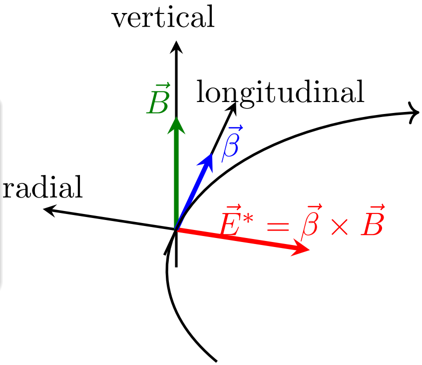
Back to Spin Motion in Storage Ring

$$\frac{d\vec{s}}{dt} = (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}} + \vec{\Omega}_{\mathrm{wind}}) \times \vec{s}$$

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m} G\vec{B},$$

$$\vec{\Omega}_{\mathrm{EDM}} = -\frac{1}{S\hbar} d\, c\, \vec{\beta} \times \vec{B},$$

$$\vec{\Omega}_{\mathrm{wind}} = -\frac{1}{S\hbar} \frac{C_N}{2f_a} (\hbar \partial_0 a(t))\, \vec{\beta},$$

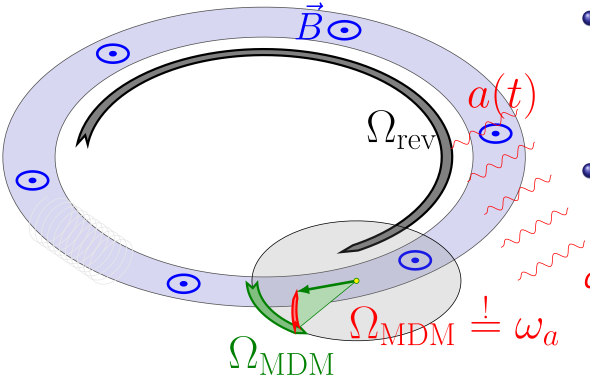


$d = d_{\mathrm{DC}} + d_{\mathrm{AC}} \cos(\omega_a t + \varphi_0)$

ocsillating EDM: $d_{AC} = a_0 g_{ad\gamma} \propto C_g$

axion field: $a(t) = a_0 \cos(\omega_a t + \varphi_0)$

Principle of storage ring axion experiment



- Axion field gives rise to an effective time-dependent θ-QCD term
- This gives rise to an oscillating electric dipole moment EDM d.

$$d = d_{DC} + d_{AC} \sin(\omega_a t + \varphi_a)$$

$$\omega_a = \frac{m_a c^2}{\hbar}$$

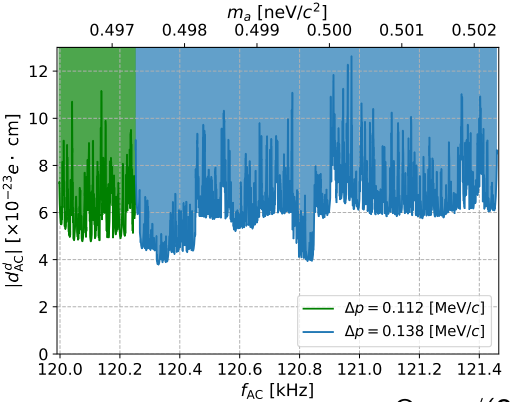
Properties of Method

- AC measurement (i.e. systematics are under control)
- axion wind effect enhanced in storage rings ($v_{\mathrm{particle}} \approx c$)

  $$\vec{\Omega}_{\mathrm{wind}} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta}$$

- One can look for ALPs at a given mass given by Ω_{MDM} or scan a certain mass range by varying Ω_{MDM}

Limits on Oscillating EDM d_{AC}, 90% CL

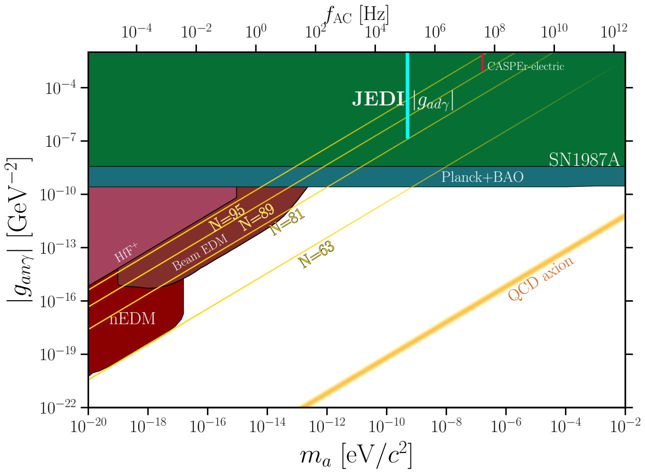


- a few days of beam time
- $$\frac{\Omega_{\mathrm{MDM}}}{2\pi} = f_{AC} = \frac{1}{2\pi}\frac{m_a c^2}{\hbar} = \gamma G f_{\mathrm{rev}}$$
- oscillating EDM < $6 \times 10^{-23} e\mathrm{cm}$

$$\equiv \Omega_{\mathrm{MDM}}/(2\pi)$$

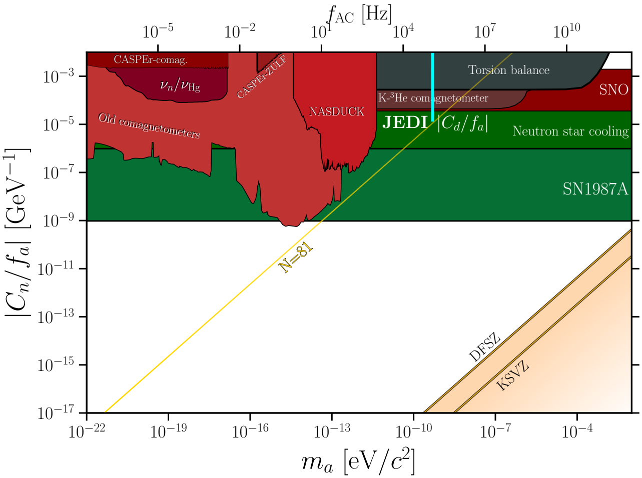
published in PRX: [15]

Axion Coupling to EDM operator $g_{ad\gamma}$ (e.g. Axion/Gluon Coupling))



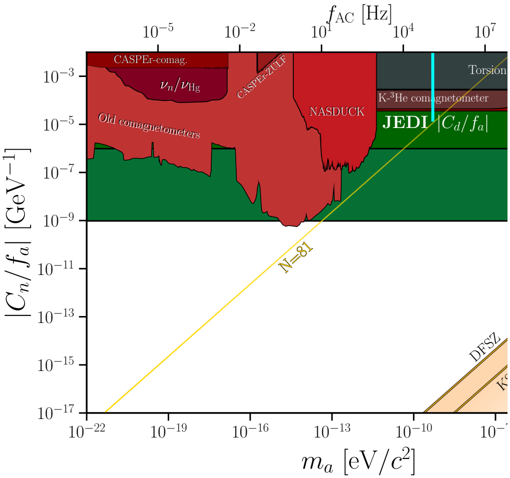
- $g_{ad\gamma} = \dfrac{d_{AC}}{a_0}$
  $a_0 = 0.55$ GeV/cm^3
  (Dark Matter is saturated by ALPs)
- assume no axion wind effect
- yellow lines (parallel to QCD axion lines): models with light QCD axion
- JEDI limit comparable or even better compared to other experiments
- Limits from SN1987A, Planck+BAO have strong model dependence

Axion Wind Effect: Coupling to Nucleons C_N/f_a



- storage ring experiments particularly sensitive to axion wind effect ($\beta = \mathcal{O}(1)$)

Axion Wind Effect: Coupling to Nucleons C_N/f_a



2023 PDG:

10 *90. Axions and Other Similar Particles*

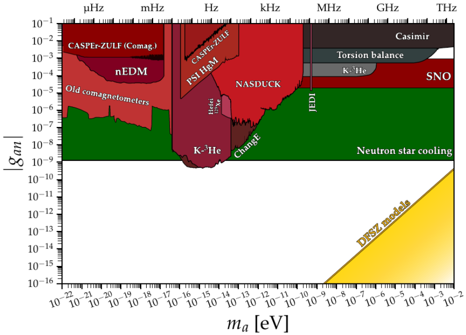
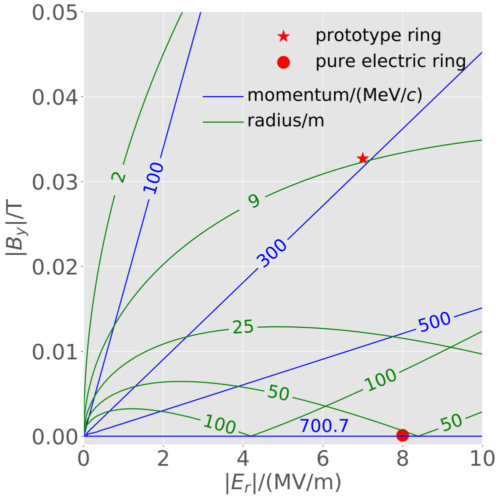


Figure 90.3: Exclusion plot for ALP-neutron coupling as described in the text. Figure courtesy of Ciaran O'Hare [61], includes data from refs. [40, 42, 206, 245–255]. The hadronic axion model prediction is given in Eq. (90.11) with vanishing quark couplings, while the DFSZ model prediction depends on $\tan\beta$ as is found in Eq. (90.12), giving the shaded yellow region above. Note that for a fine-tuned value of $\tan\beta$ g_{an} can be taken to zero. On the other hand, the neutron star cooling constraints [254] also probe the axion-proton coupling g_{ap} at a comparable level (not shown), and both g_{an} and g_{ap} cannot simultaneously be taken to zero in the DFSZ model.

Next Steps

Towards a dedicated storage ring for EDM measurements

Momentum and ring radius for proton in **frozen spin** condition



Two options:

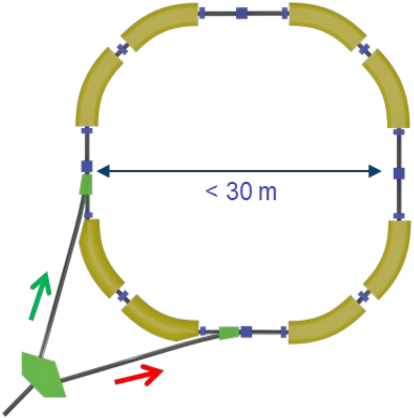
● Pure electric ring:
p = 707MeV, bending radius≈ 50 m at E=8 MV/m

⋆ combined prototype ring:
p = 300MeV, bending radius≈ 9 m at E=7 MV/m

Different Options

	☺	☹
1.) pure magnetic ring	existing (upgraded) COSY ring can be used,	lower sensitivity, precession due to G, i.e. no **frozen spin**
2.) combined ring	works for $e, p, d,$ ^{3}He, smaller ring radius	both $\vec{E}$ and $\vec{B}$ B field reversal for $\circlearrowleft, \circlearrowright$ required
3.) pure electric ring	no $\vec{B}$ field needed, $\circlearrowleft, \circlearrowright$ beams simultaneously	works only for particles with $G > 0$ (e.g. e, p)

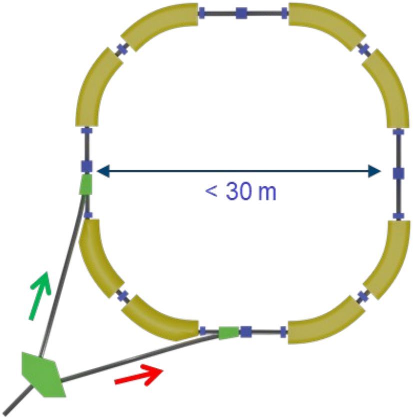
Prototype Ring: Lattice & Bending Element

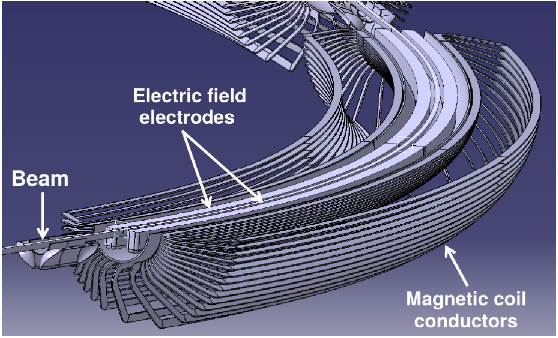


- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous ↻ and ↺ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies:
  beam cooling, deflector, beam position monitors, shielding . . .
- perform EDM measurement and axion/ALP search

[16]

Prototype Ring: Lattice & Bending Element





Summary & Outlook

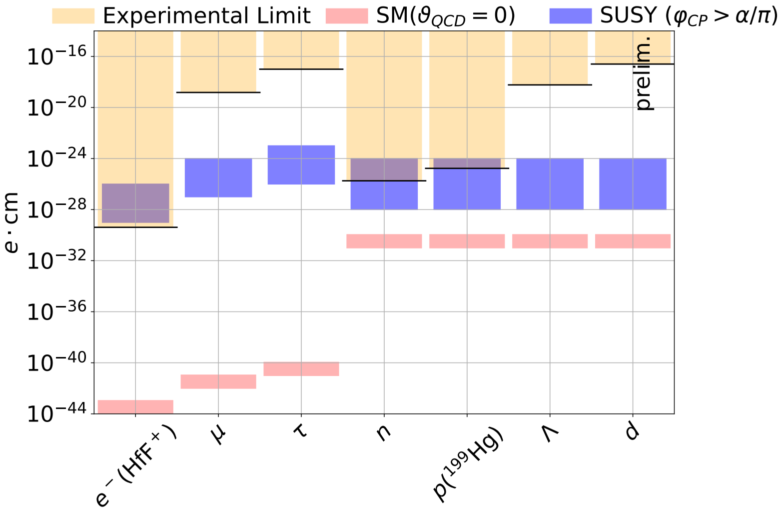
Summary & Outlook

Achievements at Cooler Synchrotron COSY at Forschungszentrum Jülich:

- large spin coherence time $\rightarrow$ observing 120kHz spin precession $\rightarrow$ feedback system on polarisation $\rightarrow$ build-up of vertical polarisation observed
- first measurement of deuteron EDM
- first search for axion-like particle in storage ring

- precision limited because of magnetic storage ring
- future: Dedicated storage ring needed

EDM limits



Experimental Limit
SM($\vartheta_{QCD} = 0$)
SUSY ($\varphi_{CP} > \alpha/\pi$)
10^{-16}
10^{-20}
10^{-24}
10^{-28}
10^{-32}
10^{-36}
10^{-40}
10^{-44}
$e \cdot cm$
prelim.
e^- (HfF$^+$)
μ
τ
n
p(^{199}Hg)
Λ
d

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