Spin Polarisation Experiments at Storage Rings: Axion Searches and Electric Dipole Moments

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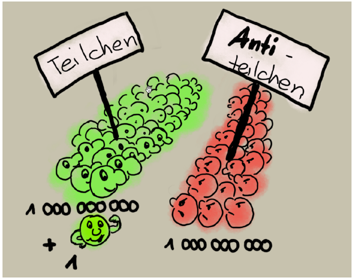
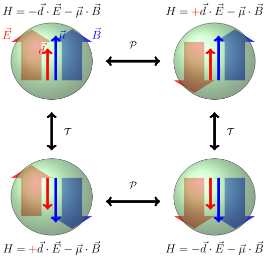
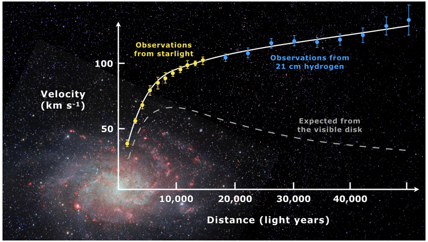
Motivation

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

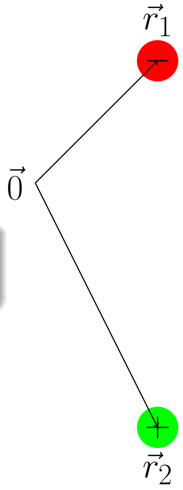
- **Introduction:**
  Electric Dipole Moments and connection to axions/ALPs
- **Experimental Methods for charged particles**
  Observing Spin precession
- **Experiments & Results:**
  on permanent & oscillating electric dipole moments

Introduction

Electric Dipoles

Classical definition:

$$\vec{d} = \sum_i q_i \vec{r}_i$$



Order of magnitude

	atomic physics	hadron physics
charges	e	
$\|\vec{r}_1 - \vec{r}_2\|$	1 Å= 10^{-8}cm	
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	
observed	water molecule $4 \cdot 10^{-9} e \cdot$ cm	

Order of magnitude

	atomic physics	**hadron physics**
charges	e	e
$\lvert\vec{r}_1 - \vec{r}_2\rvert$	1 Å= 10^{-8}cm	$1\,\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$4 \cdot 10^{-9} e\cdot$ cm	$< 1.8 \cdot 10^{-26} e\cdot$ cm

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

$\vec{d}$ is odd under parity transformation ($\vec{r} \rightarrow -\vec{r}$):

$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

Consequences:
In a state $|a\rangle$ of given parity the expectation value is 0:

$$\left\langle a|\vec{d}|a\right\rangle = -\left\langle a|\vec{d}|a\right\rangle = 0$$

but if $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$
in general $\left\langle a|\vec{d}|a\right\rangle \neq 0 \Rightarrow$ i.e. molecules

Order of magnitude

Molecules can have large EDM because of degenerated ground states with different parity

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Elementary particles (including hadrons) have a definite parity and cannot posses an EDM
$P|\text{had}>= \pm 1|\text{had}>$

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Elementary particles (including hadrons) have a definite parity and cannot posses an EDM
$P|\text{had}>= \pm 1|\text{had}>$

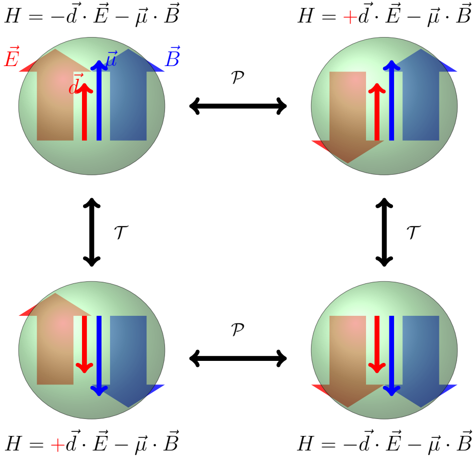
unless

$\mathcal{P}$ and time reversal $\mathcal{T}$ invariance are violated!
In this case: $|\text{had}>= |P=+>+\epsilon|P=->$

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

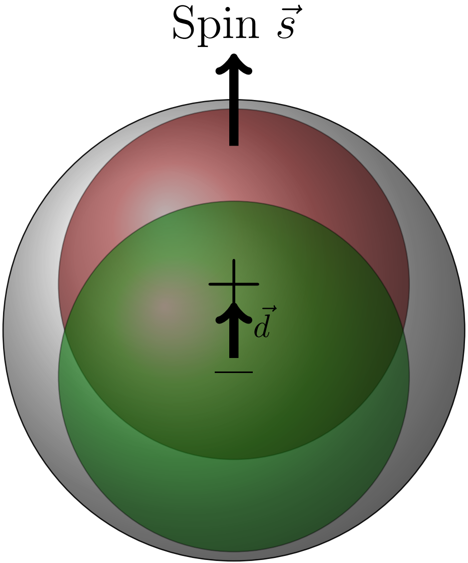
$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment (MDM)
both || to spin $\vec{s}$

	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)



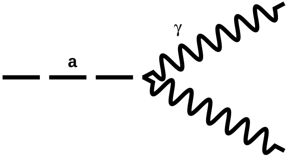
- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \overset{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to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

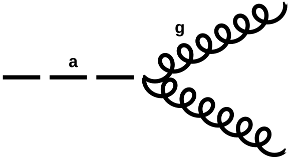
Axions/Axion Like Particles (ALPs)

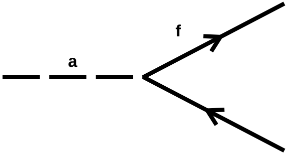
- hypothetical pseudoscalar elementary particle postulated by Peccei,Quinn,Wilczek,Weinberg to resolve the strong CP problem
- axion are also Dark Matter candidates
- axion like particles (ALP): similar properties as axions, (but ALPs don’t solve the strong QCD problem)
- huge experimental effort to 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

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







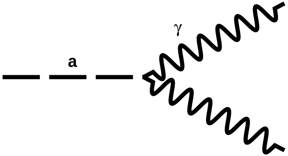
oscillating
Electric Dipole Moment (oEDM)

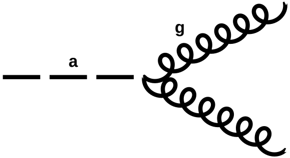
axion wind term

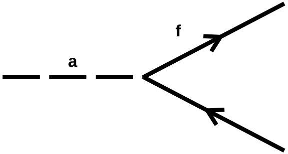
For low axion masses, if axions saturate dark matter they can be described by classical field: $a(t) = a_0 \cos(\omega_a t + \varphi_a)\,, \quad m_a c^2 = \hbar\omega_a\,, \quad$ Coupling $\propto \frac{1}{f_a} \propto m_a$ [1]

Axion Coupling

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







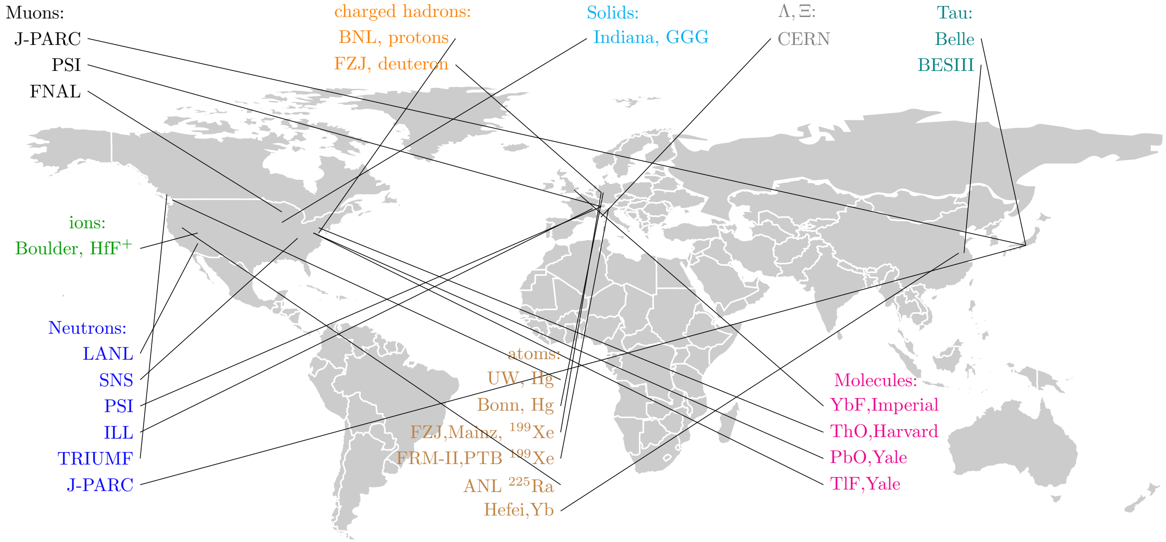
studied by many experiments [1]

oscillating Electric Dipole Moment (oEDM)

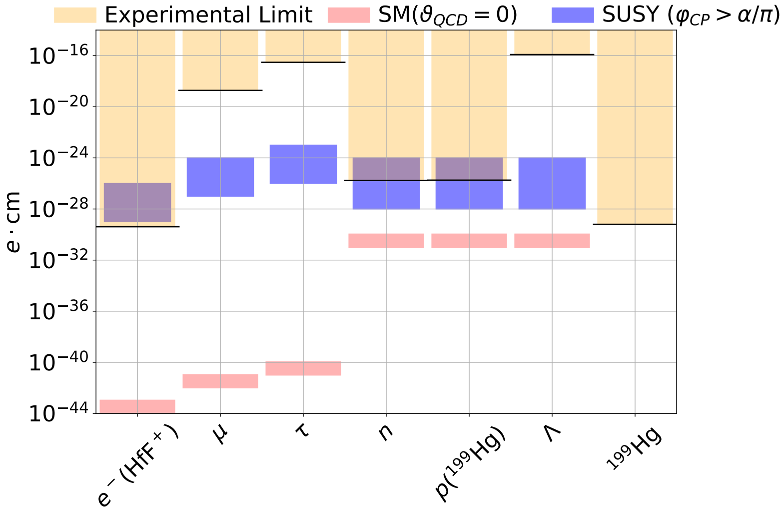
axion wind term

accessible in storage ring experiments with spin polarized beams

EDM Experiments/Activities around the world

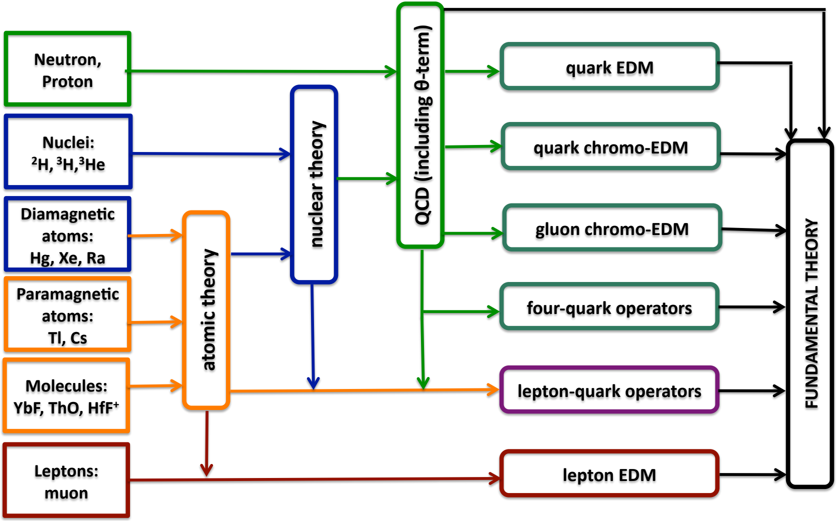


Results



Impressive Limits, but no finite EDM found yet. No direct measurement on charged hadrons.

Why EDMs for many different particle species?



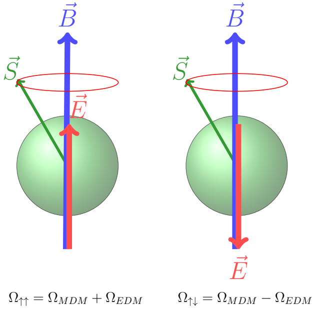
J. de Vries

Experimental Methods

Experimental Method

Observe Spin Precesison 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:

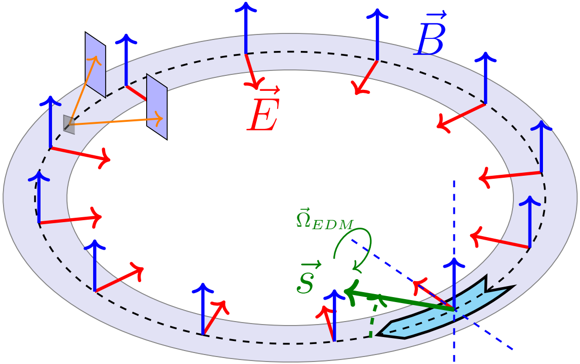
Neutron in earth B-field: $\Omega \approx 9000\,\mathrm{s}^{-1}$

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

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

Even more complicated for charged particles:

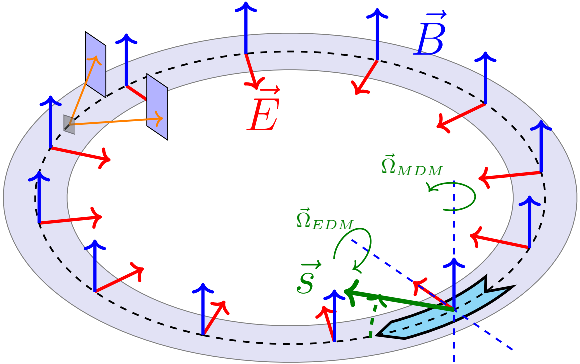
Experimental Method for charged particle: Storage Ring



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

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

Experimental Method for charged particle: Storage Ring



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

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 $\vec{s}_{horz} || \vec{p}$ (**frozen spin**)

Spin Precession: Thomas-BMT Equation

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

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, $G \approx 1.79$ for protons

Spin Precession: Thomas-BMT Equation

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

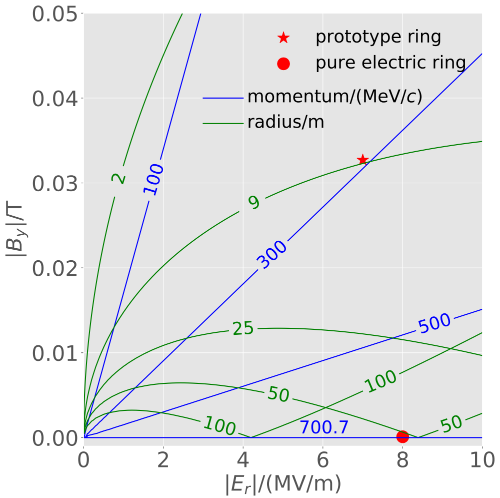
$\vec{\Omega}_{\mathrm{MDM}} = 0\,,$ **frozen spin** $= \vec{\Omega}_{\mathrm{EDM}}$

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

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

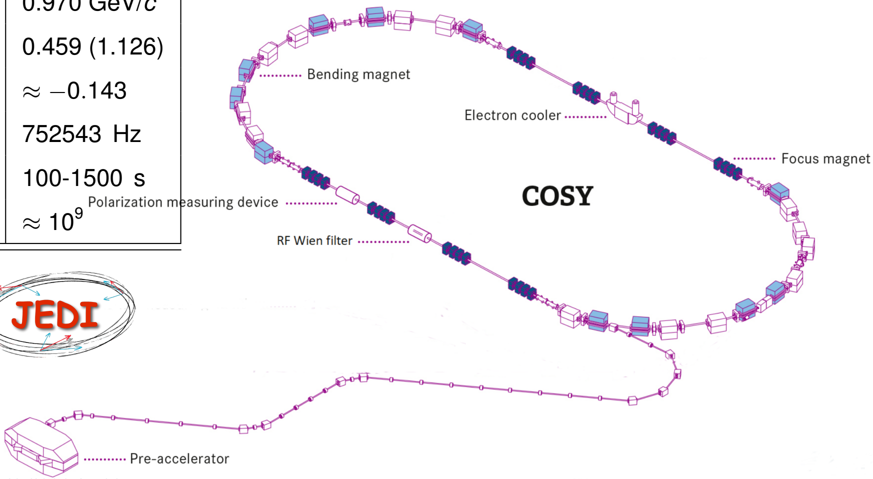
Different Options

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

Experiments & Results

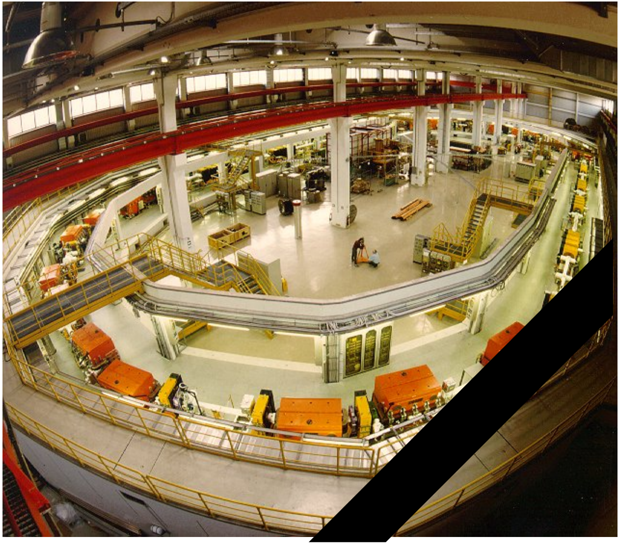
Precursor Experiment

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,

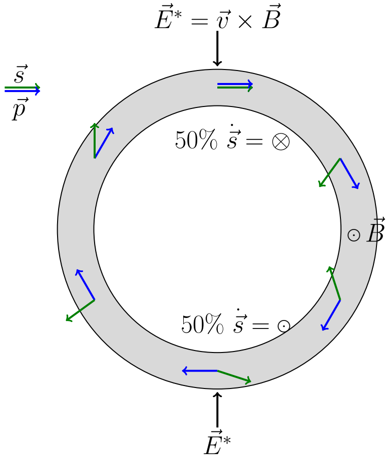
COoler SYnchrotron COSY



- pol. deuteron beam $p \approx 970\text{MeV}/c$
- polarization $P \approx 0.40$
- $\approx 10^9$ stored particles per 300 s cycle
- $\Omega_{\text{MDM}} \approx 2\pi \cdot 120\,\text{kHz}$
- JEDI (Jülich Electric Dipole moment Investigations) collaboration

Principle of EDM measurement at magnetic storage ring

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is || to momentum, 50% of the time it is anti-||.



E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

Principle of EDM measurement at magnetic storage ring

Problem:

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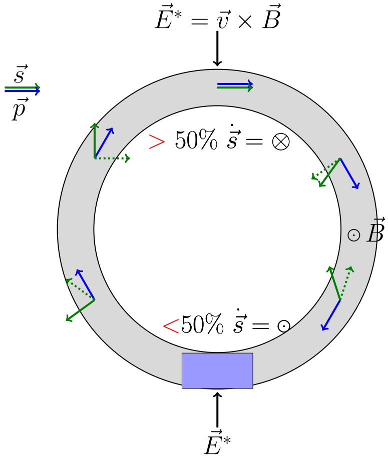


E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

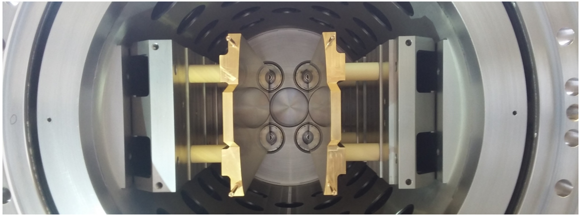
Use resonant “magic Wien-Filter” in ring ($\vec{E}_W + \vec{v} \times \vec{B}_W = 0$):

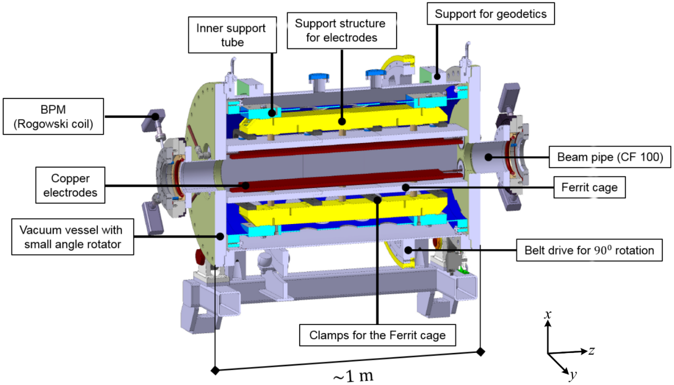
$E^*_W = 0 \rightarrow$ part. trajectory is not affected but

$B^*_W \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **net EDM effect can be observed!**

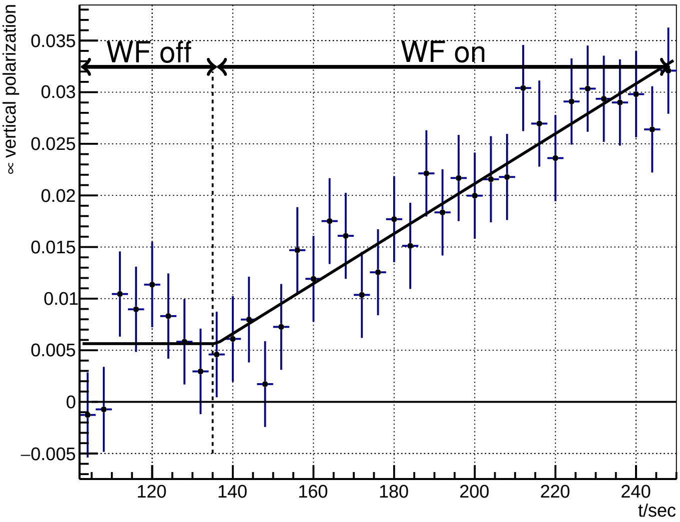
Wien filter





- field: $2.7 \cdot 10^{-2}$Tmm for 1kW input power
- frequency range: 100 kHz-2MHz

Observation of polarization build-up



- radio-frequency Wien filter (WF) provides partially frozen spin
- polarization build-up proportional to EDM . . . and many perturbations
- perturbations are under investigation

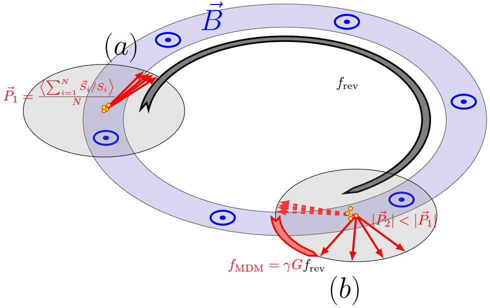
Precursor Experiment at COSY

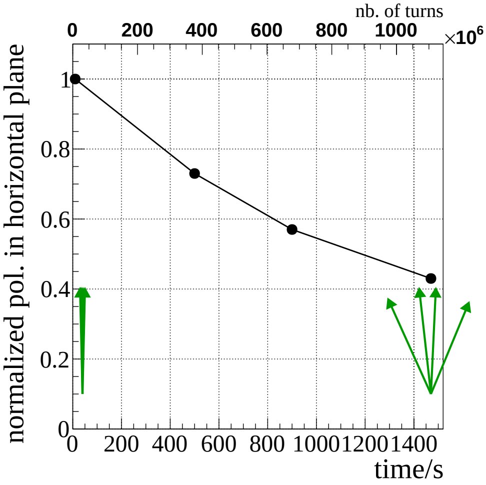
Tools developed to manipulate and measure beam polarization:

- 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
- Single bunch spin manipulation
- RF Wien filter, BPMs, deflector, polarimeter, ...

Long Spin Coherence Time (SCT)

Long Spin Coherence time > 1000 s reached





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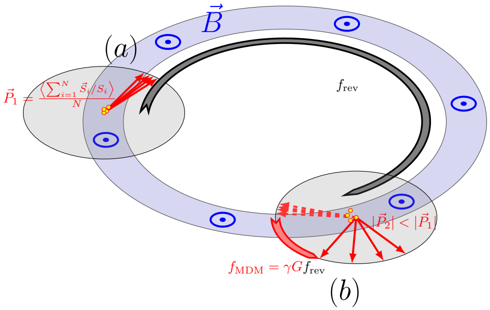
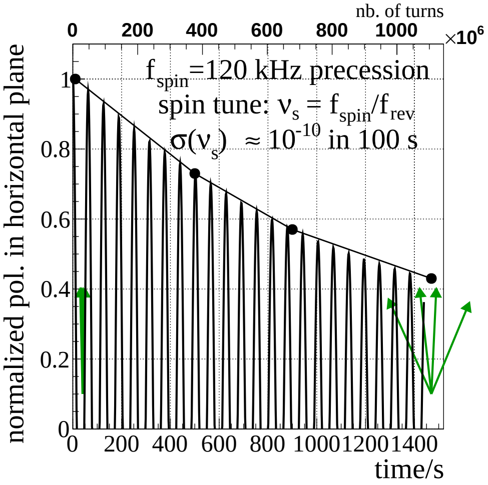
Long Spin Coherence Time (SCT)

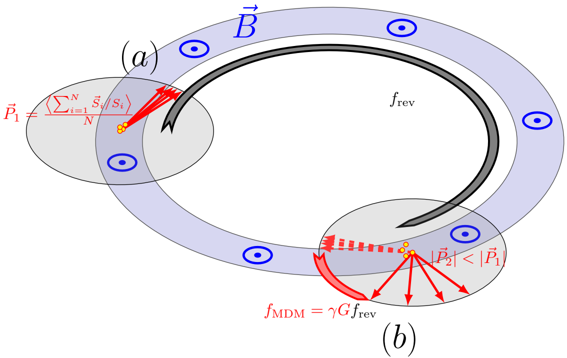
Long Spin Coherence time > 1000 s reached

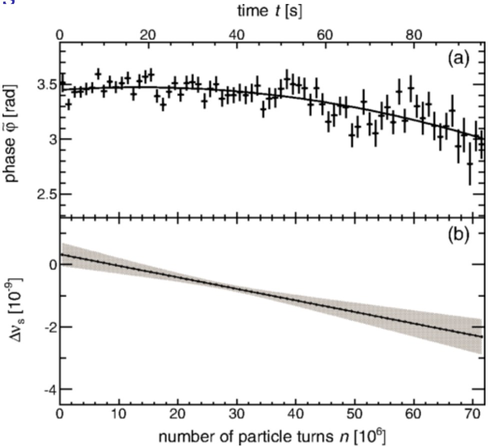




[2]

Spin Tune ν_s





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

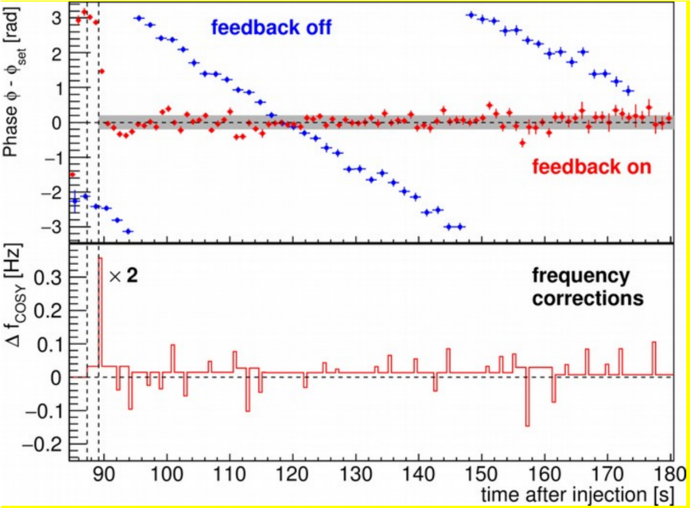
$\sigma(\nu_s = \gamma G) \approx 10^{-10}$ in 100 s

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

[3]

Polarisation feedback

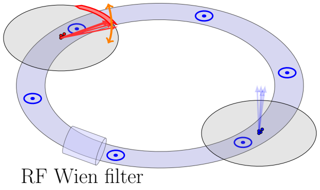
Controlling 120kHz precession

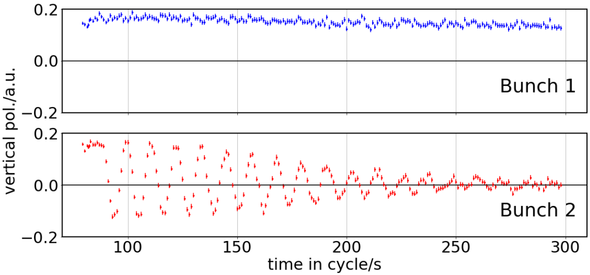


[4]

Pilot Bunch

Two bunches in storage ring, only one is manipulated by Wien filter





Axion Searches

Spin Motion in Storage Ring

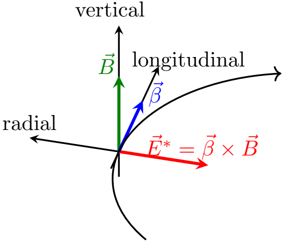
$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{\rm MDM} + \vec{\Omega}_{\rm EDM} + \vec{\Omega}_{\rm wind}) \times \vec{S}$$

$$\vec{\Omega}_{\rm MDM} = -\frac{q}{m} G\vec{B} \quad , \qquad \vec{\mu} = g\frac{q\hbar}{2m}\vec{S} = (1+G)\frac{q\hbar}{m}\vec{S}$$

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

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

$$|\vec{\Omega}_{\rm MDM}| \gg |\vec{\Omega}_{\rm EDM}|, |\vec{\Omega}_{\rm wind}|$$



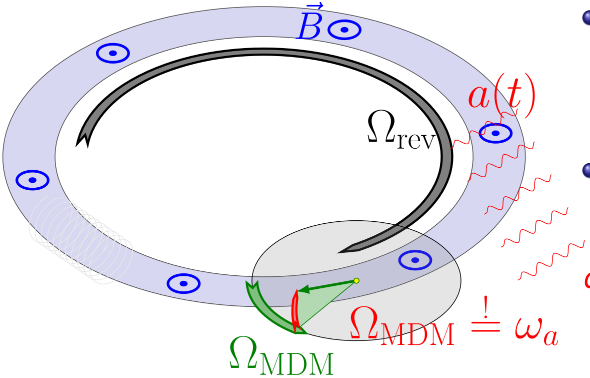
axion field: $a(t) = a_0 \cos(\omega_a t + \varphi_0)$ $\quad d = d_{\rm DC} + d_{\rm AC} \cos(\omega_a t + \varphi_0)$ (EDM)

$\hbar\omega_a = m_a c^2$ $\quad d_{AC} = a_0 g_{ad\gamma} \propto C_g$

oscillating EDM ↗ ↖ ALP-EDM coupling

[5, 6, 7]

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.

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

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

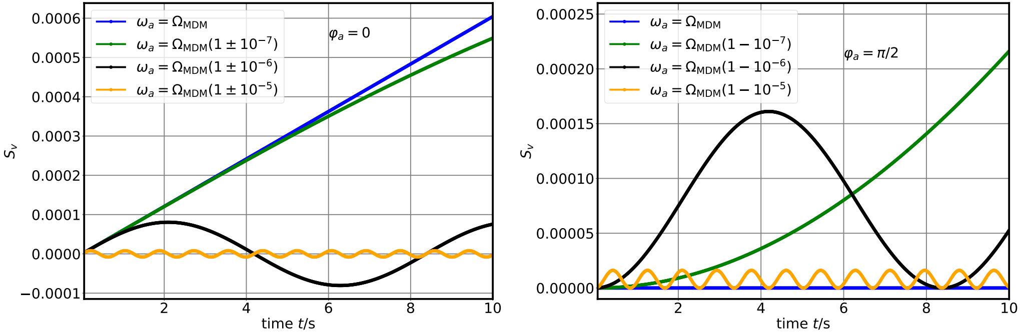
Properties of Method

- 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}

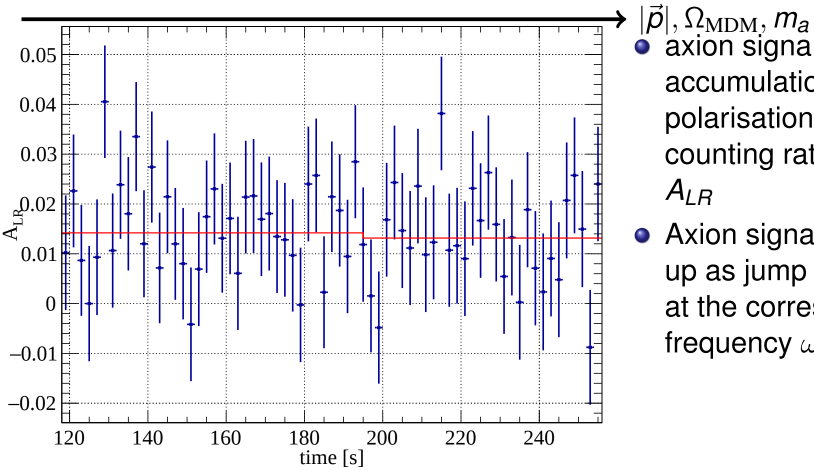
Expected Build-up

$a(t) = a_0 \cos(\omega_a t + \varphi_a)$ axion phase φ_a not known!
If your are unlucky, build-up is zero.



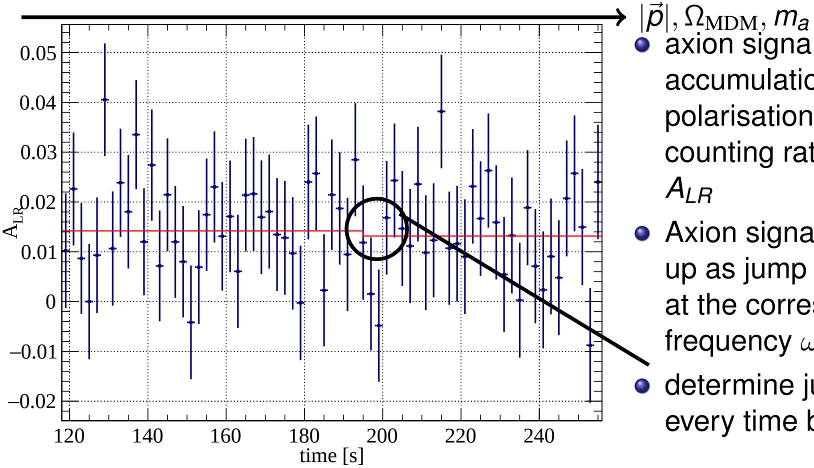
Remedy: Inject 4 pulses with 90 degree polarisation phase difference.
$\rightarrow$ You cannot miss the signal.

Left-Right Asymmetry $A_{LR} \propto P_V$ Scan



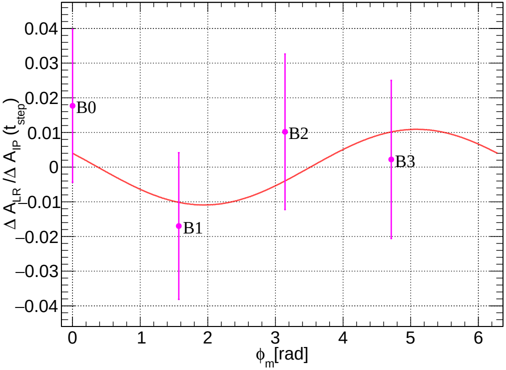
- axion signal $\propto$ accumulation of vertical polarisation $\propto$ left-right counting rate asymmetry, A_{LR}
- Axion signal would show up as jump in asymmetry at the corresponding frequency $\omega_a \propto m_a$

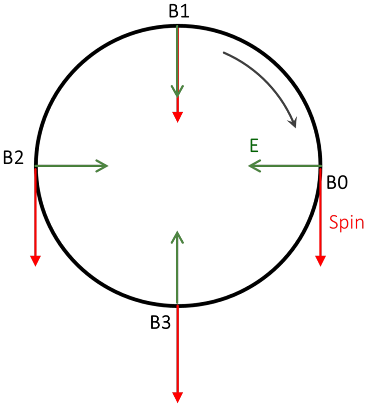
Left-Right Asymmetry $A_{LR} \propto P_V$ Scan



- axion signal $\propto$ accumulation of vertical polarisation $\propto$ left-right counting rate asymmetry, A_{LR}
- Axion signal would show up as jump in asymmetry at the corresponding frequency $\omega_a \propto m_a$
- determine jump ΔA_{LR} for every time bin

Typical Asymmetry Measurement

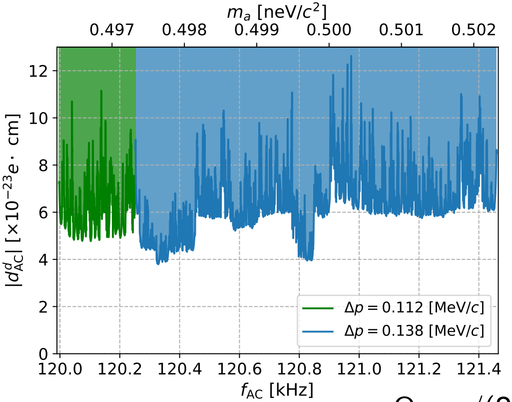




Fit: $f(\Phi_m) = C_1 \cos(\Phi_m) + C_2 \sin(\Phi_m)$

$\hat{A} = \sqrt{C_1^2 + C_2^2}$

Results on Oscillating EDM d_{AC}, 90% CI

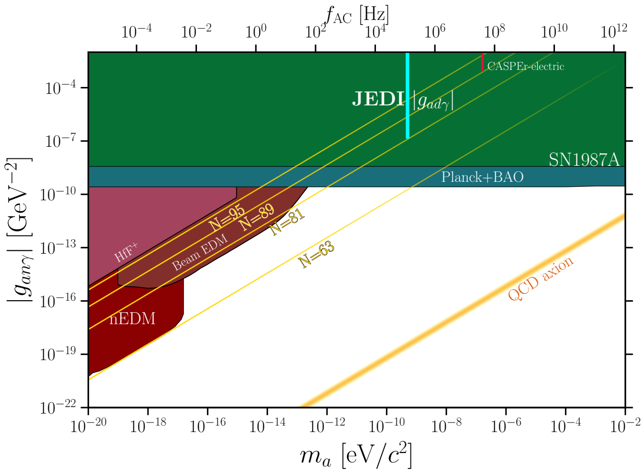


$\equiv \Omega_{\mathrm{MDM}}/(2\pi)$

- a few days of beam time
- $$\frac{\Omega_{\mathrm{MDM}}}{2\pi} = f_{AC} = \frac{1}{2\pi}\frac{m_a c^2}{\hbar} = \gamma G f_{\mathrm{rev}}$$

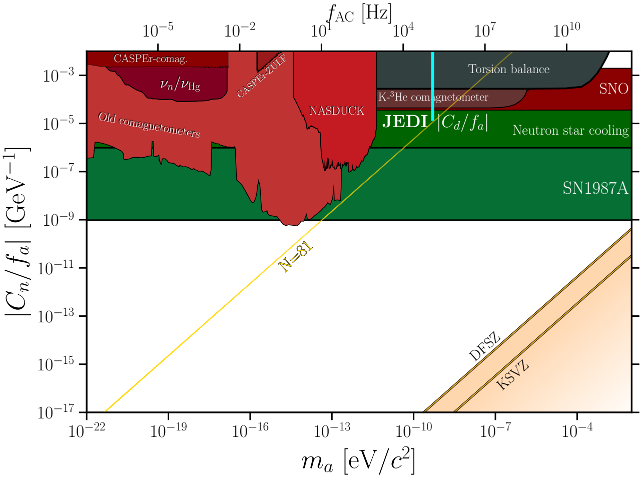
published in PRX: [8]

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

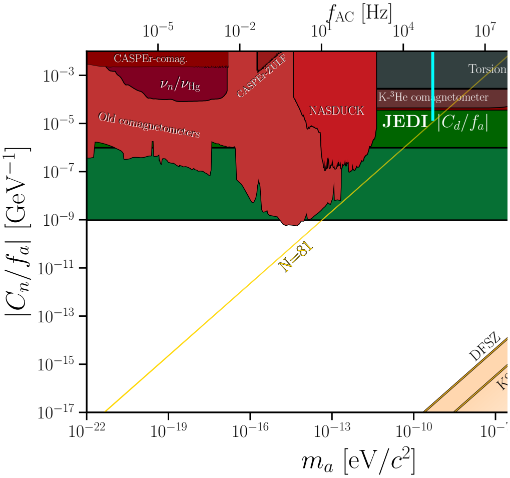
Axion Wind Effect: Coupling to Nucleons C_N/f_a



- 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**

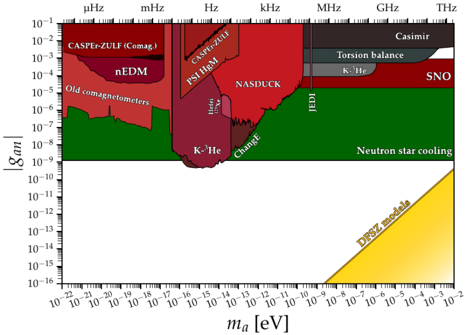


Figure 90.3: Exclusion plot for ALP-neutron coupling as described in the text. Figure courtesy of Ciaran O'Hare [61], includes data from refs. [40, 42, 206, 245–255]. The hadronic axion model prediction is given in Eq. (90.11) with vanishing quark couplings, while the DFSZ model prediction depends on tan β as is found in Eq. (90.12), giving the shaded yellow region above. Note that for a fine-tuned value of tan β 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.

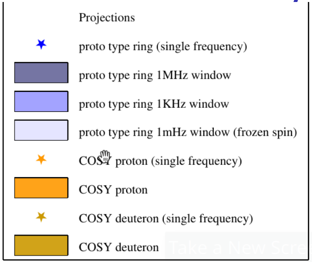
How to Explore a Wider Mass Range m_a

Up to now experiment was performed in a very narrow frequency range. How to access wider mass range?

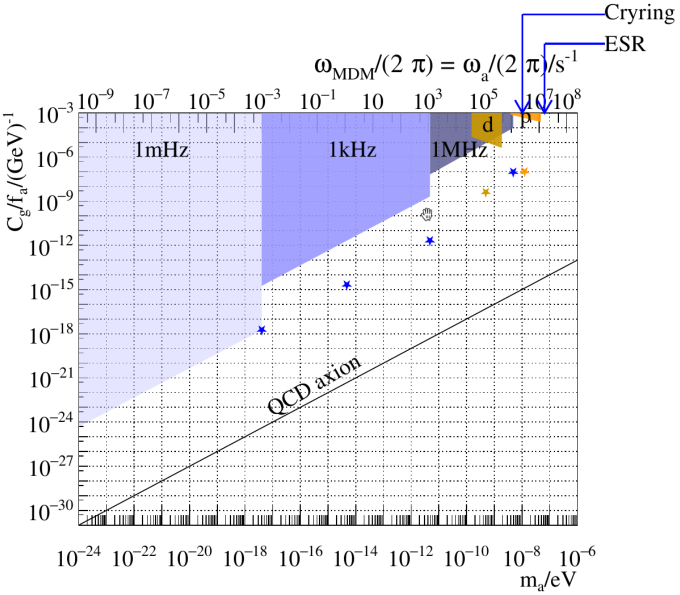
$$\Omega_{\mathrm{MDM}} = \gamma G \Omega_{rev}$$

1. modify beam energy (changes γ, Ω_{rev})
2. use different nuclei (changes G)
3. Use additional electric field
   $$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$
   allows to reduce $\vec{\Omega}_{\mathrm{MDM}}$ down to 0

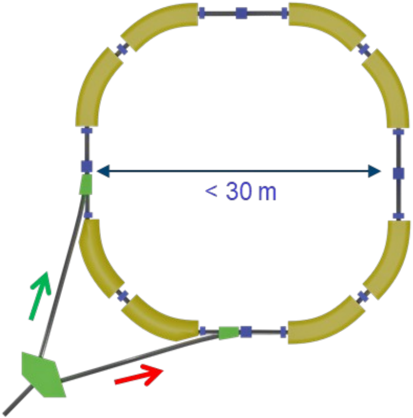
Axion Searches at Storage Rings



Estimate for one year (10^7 seconds) running time [9] for COSY and a prototype storage ring for EDM measurements



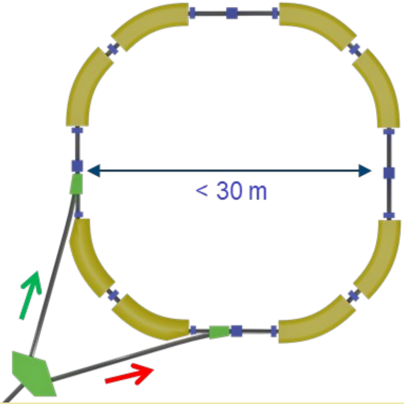
Prototype Ring: Lattice & Bending Element

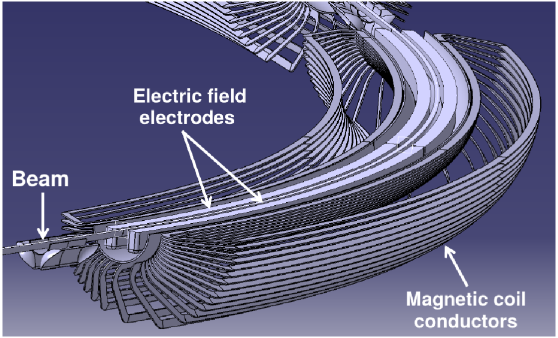


- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous ↻ and ↺ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies:
  beam cooling, deflector, beam position monitors, shielding . .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

[10]

Prototype Ring: Lattice & Bending Element





Pathfinder Facility for a new Class of **Pre**cision Physics **Sto**rage Rings (PRESTO) proposal to EU in preparation
Partner: INFN, GSI/FZJ, CERN, MPG, RWTH, LIV, JAG, TSU

Summary

Summary

- Spin polarisation experiments in storage rings offer new possibilities to search for Electric Dipole Moments and axions/ALPs
- First results obtained at Cooler Synchrotron COSY at Forschungszentrum Jülich for deuterons on ALP searches and deuteron EDM
- Future: Dedicated storage ring needed

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Extra Slides

EDM: SUSY Limits

electron:

MSSM: $\varphi \approx 1 \Rightarrow d = 10^{-24} - 10^{-27} e\cdot\text{cm}$

$\varphi \approx \alpha/\pi \Rightarrow d = 10^{-26} - 10^{-30} e\cdot\text{cm}$

hadron:

MSSM: $d = 10^{-24} e\cdot\text{cm} \cdot \sin\phi_{CP} \dfrac{200\text{GeV}}{M_{SUSY}}$

SM EDM values

$$\mu_n = \frac{e}{2m_p} \approx 10^{-14} e\text{cm (CP \& P conserving)}$$

$$d_n = 10^{-14} \times \underbrace{10^{-7}}_{P-violation} \times \underbrace{10^{-3}}_{CP-violation} \times \underbrace{G_F F_\pi}_{\text{no flavor change}} = 10^{-31} e\text{cm}$$

$$\begin{aligned} d_n &= \mathcal{O}(g_w^4 g_s^2) = \mathcal{O}(G_F^2 g_s^2) \quad (3\,loop) \\ d_e &= \mathcal{O}(g_w^6 g_s^2) = \mathcal{O}(G_F^3 g_s^2) \quad (4\,loop) \end{aligned}$$

Statistical Sensitivity

beam intensity	$N = 4 \cdot 10^{10}$ per fill
polarization	$P = 0.8$
spin coherence time	$\tau = 1000\,\mathrm{s}$
electric fields	$E = 8\,\mathrm{MV/m}$
polarimeter analyzing power	$A = 0.6$
polarimeter efficiency	$f = 0.005$

$$\sigma_{\text{stat}} \approx \frac{2\hbar}{\sqrt{Nf\tau}PAE} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 2.4 \cdot 10^{-29}\ e\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

Systematic Sensitivity

signal: $\Omega_{\mathrm{EDM}} = \frac{dE}{s\hbar} = 2.4 \cdot 10^{-9}\,\mathrm{s}^{-1}$ for $d = 10^{-29}\,e\,\mathrm{cm}$

- radial B-field of $B_r = 10^{-17}\,\mathrm{T}$:
  $\Omega_{B_r} = \frac{eGB_r}{m} = 1.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$
- geometric Phases (non-commutation of rotations), $B_{\mathrm{long}}, B_{\mathrm{vert}} \approx 1\,\mathrm{nT}$
  $\Omega_{\mathrm{GP}} = \left(\frac{eGB}{16m}\right)^2 \frac{1}{f_{\mathrm{rev}}} = 3.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$
- General Relativity:
  $\Omega_{\mathrm{GR}} = -\frac{\gamma}{\gamma^2 + 1} \frac{\beta g}{c} = -4.4 \cdot 10^{-8}\mathrm{s}^{-1}$
- …

Systematic Sensitivity

Remedy:

$$\circlearrowright: \quad \Omega_{\mathrm{CW}} = \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}} + \Omega_{B_r}\,,$$

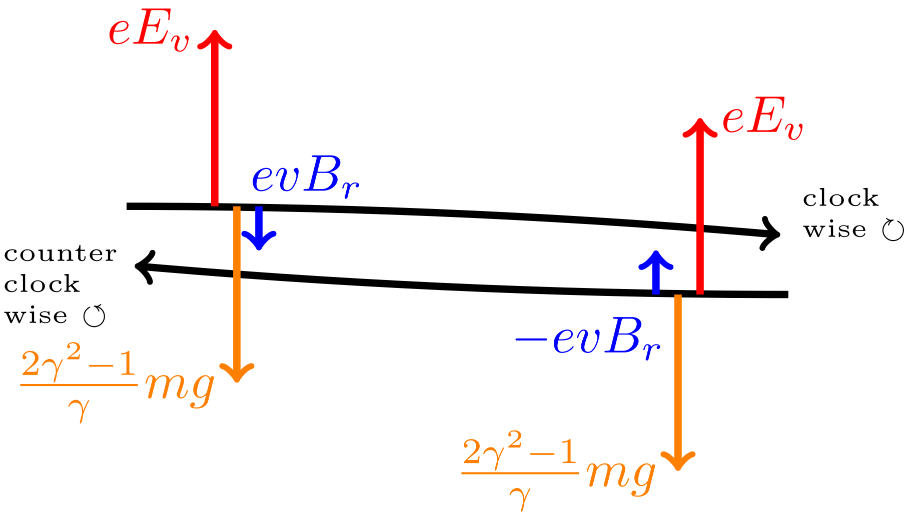
$$\circlearrowleft: \quad \Omega_{\mathrm{CCW}} = \Omega_{\mathrm{EDM}} - \Omega_{\mathrm{GP}} - \Omega_{\mathrm{GR}} + \Omega_{B_r}\,.$$

$\Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}}$ drops out in sum, $\Omega_{\mathrm{CW}} + \Omega_{\mathrm{CCW}}$, effect of B_r can be subtracted by observing displacement of the two beams.

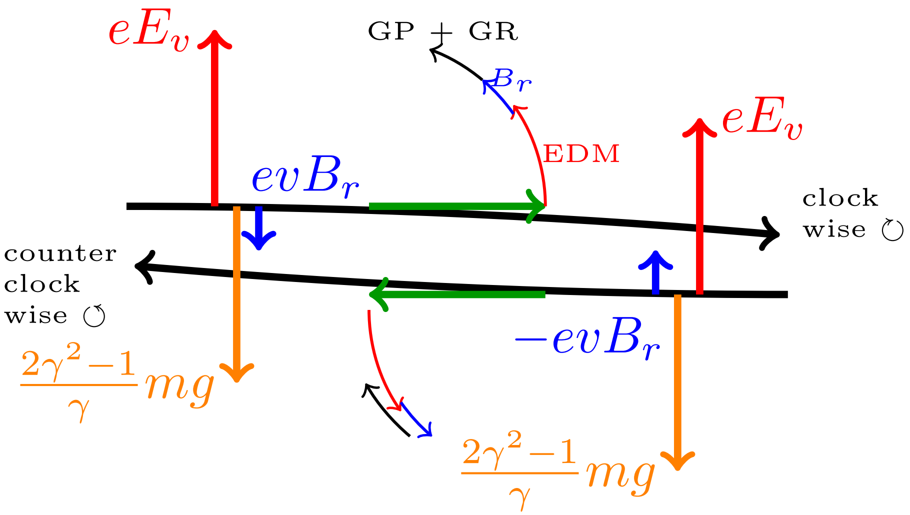
Conclusion:

Statistically one can reach sensitivity of $\approx 10^{-29}\,e\,\mathrm{cm}$, many systematic effects can be controlled using $\circlearrowleft$ and $\circlearrowright$ beams, needs further investigation
$\rightarrow$ **staged approach**

Systematics



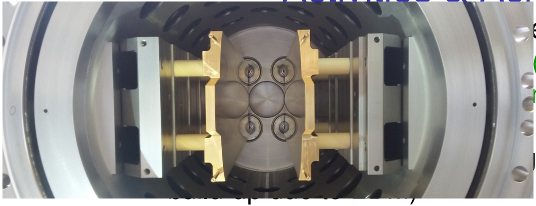
Systematics



Activities & Achievements at COSY

- required for first EDM measurement:
  - maximize spin coherence time (SCT)
  - precise measurement of spin precession (spin tune)
  - polarization feed back
  - RF- Wien filter (needed in magnetic storage ring to observe polarization build-up due to EDM)
- to reduce systematic errors:
  - development of high precision beam position monitors
  - beam based alignment
- Interpretation of results:
  - theory (pEDM, dEDM, nEDM, . . . $\rightarrow$ underlying theory)
  - spin tracking simulation (measured polarization $\rightarrow$ EDM)
- Design of dedicated storage ring:
  - accelerator lattice
  - polarimeter development
  - development of (electro static) deflectors
- other observables:
  - axion searches, general relativity

Activities & Achievements at COSY



ent:

(SCT)

recession (spin tune)

netic storage ring to observe polarization

- to reduce systematic errors:
  - development of high precision beam position monitors
  - beam based alignment
- Interpretation of results:
  - theory (pEDM, dEDM, nEDM, . . . $\rightarrow$ underlying theory)
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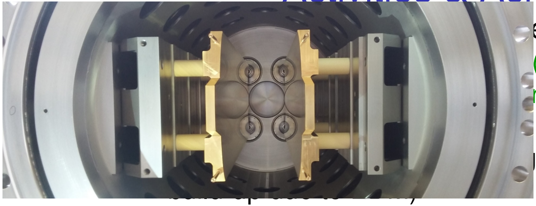
Activities & Achievements at COSY



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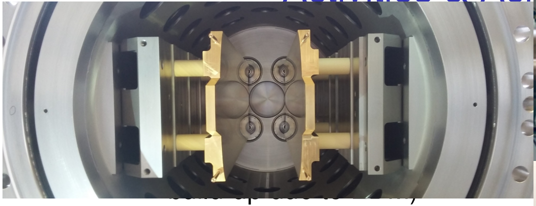

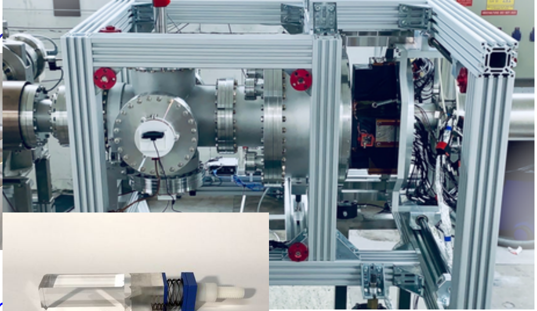

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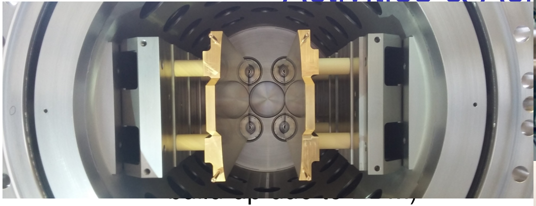
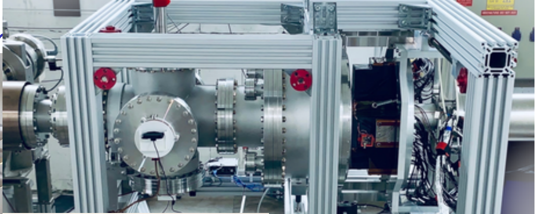
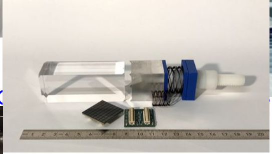
Activities & Ach





- to reduce systematic errors:
  - development of high precision b



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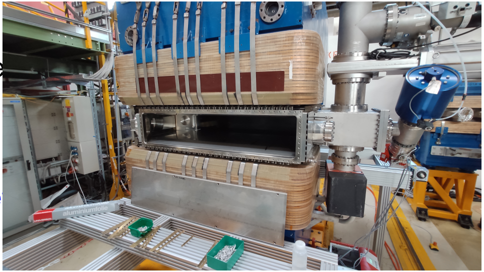
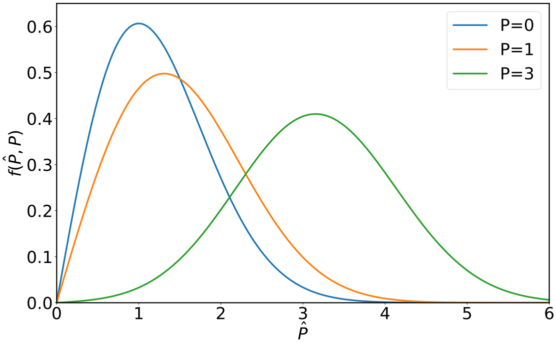


- axion searches, general relativity

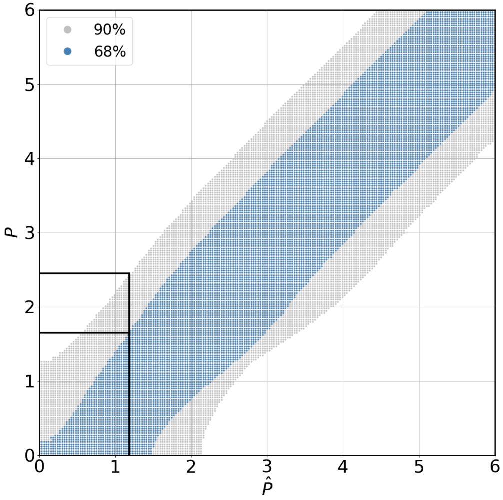
Problem

Fit will always find an amplitude ($\hat{A} \geq 0$), now use $\hat{P} = \dfrac{\hat{A}}{\sigma}$, $\quad \sigma$: uncertainty

$$f(\hat{P}|P)\,\mathrm{d}\hat{P} = e^{-\frac{\hat{P}^2+P^2}{2}}\,\hat{P} I_0(\hat{P}P)\,\mathrm{d}\hat{P},$$ Rice distribution



$\hat{P} = \hat{A}/\sigma \rightarrow$ Confidence Interval



- procedure based on Feldman-Cousins methods [11]
- on horizontal axis read off the measured $\hat{P}$
- vertical axis gives lower and upper limit for true P
- limit on P directly related to limit on d_{AC}

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

$G = 0.001159652$