Electric Dipole Measurements at Storage Rings

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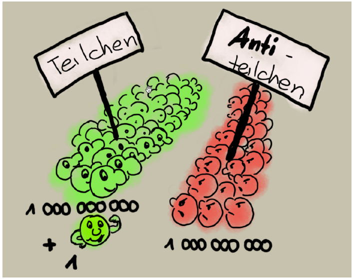
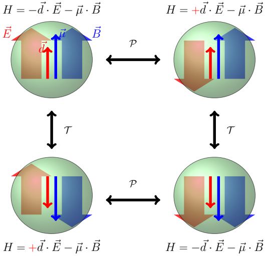
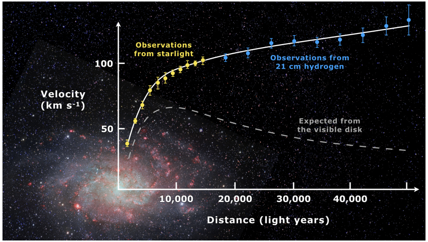
Motivation

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?

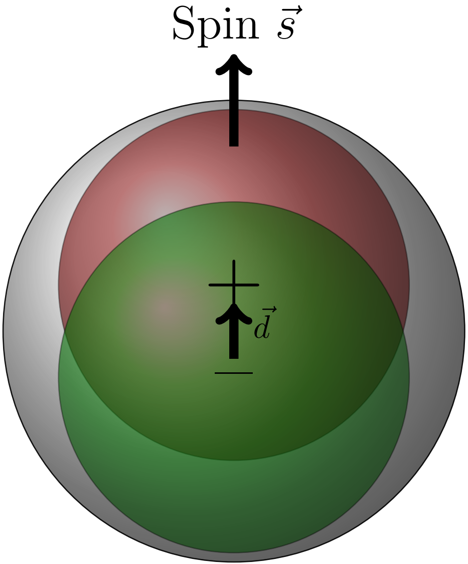






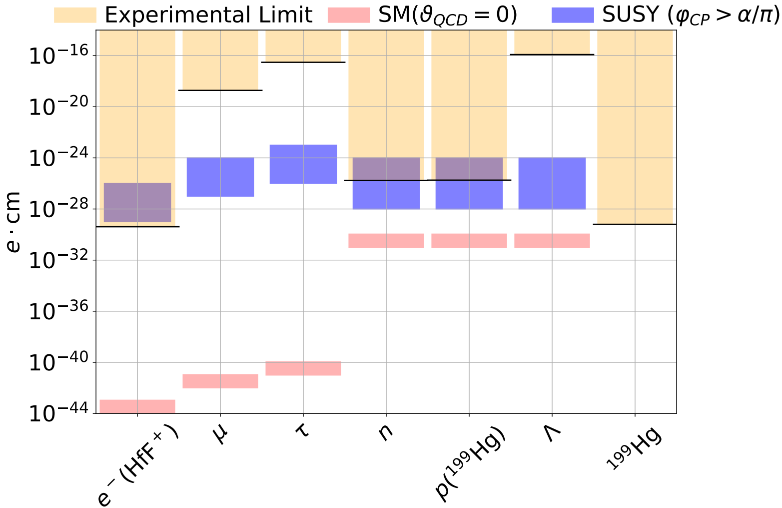
source:M. De Leo, Wikipedia

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
  $d = d_{DC} + d_{AC} \cos(\omega_a t + \varphi_a)$
  $m_a c^2 = \hbar \omega_a$

Results on (static) EDMs (d_{DC})

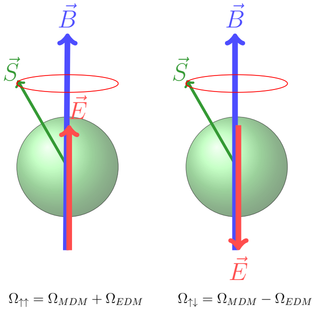


Impressive Limits, but no finite EDM found yet. No direct measurement on charged hadrons.

Experimental Method

Observe Spin Precessison 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:

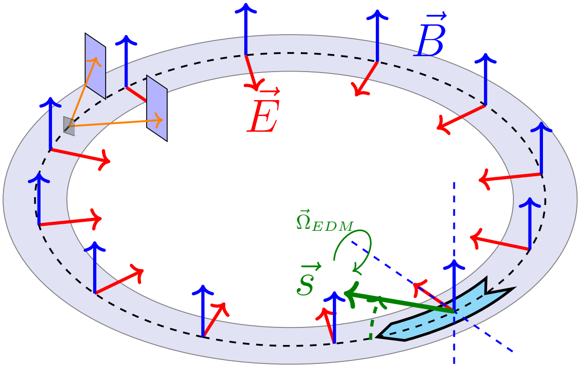
Neutron in earth B-field: $\Omega \approx 9000\,\mathrm{s}^{-1}$

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

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

Even more complicated for charged particles:

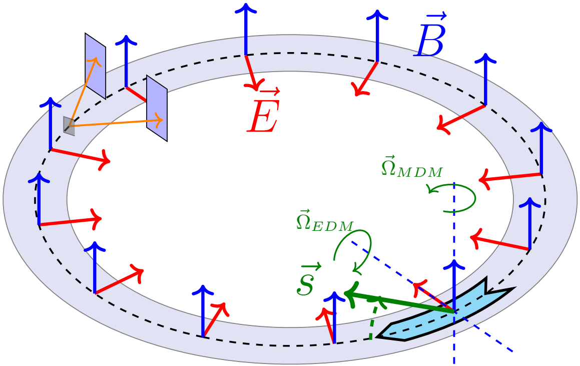
Experimental Method for charged particle: Storage Ring



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

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{horz} || \vec{p}$ (**frozen spin** , $\vec{\Omega}_{\mathrm{MDM}} = 0$)

Experimental Method for charged particle: Storage Ring



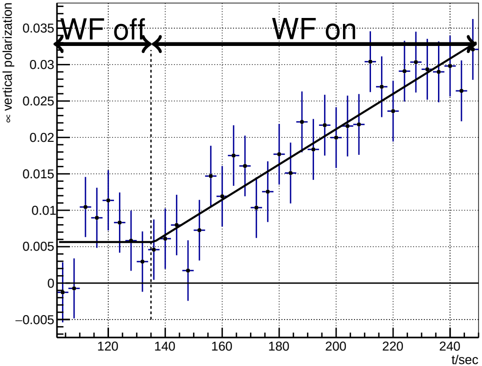
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \underbrace{d(\vec{E} + \vec{v} \times \vec{B}) \times \vec{s}}_{= \vec{\Omega}_{\mathrm{EDM}}}$$

In general:

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

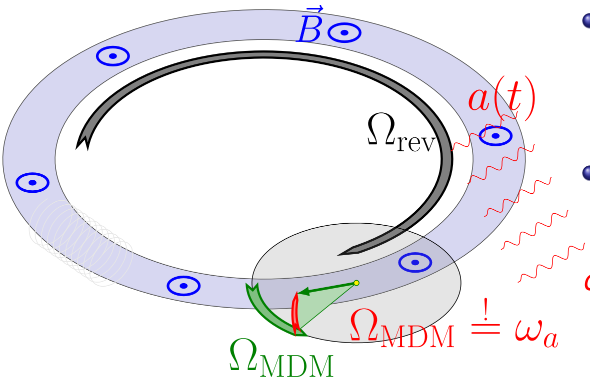
build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{horz} || \vec{p}$ (**frozen spin** , $\vec{\Omega}_{\mathrm{MDM}} = 0$)

Results from Cooler Synchrotron COSY



- partially frozen-spin condition realized using a radio-frequency Wien filter
- Polarisation Build-up observed dominated by systematics

Principle of storage ring axion experiment

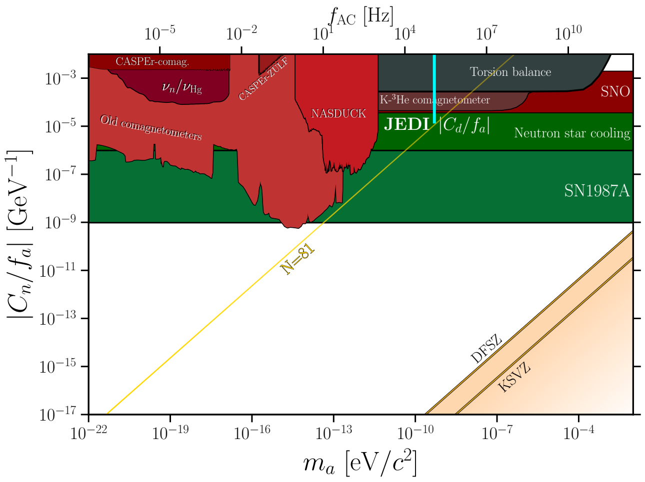


- Axion field gives rise to an effective time-dependent θ-QCD term
- This gives rise to an oscillating electric dipole moment EDM d.

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

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

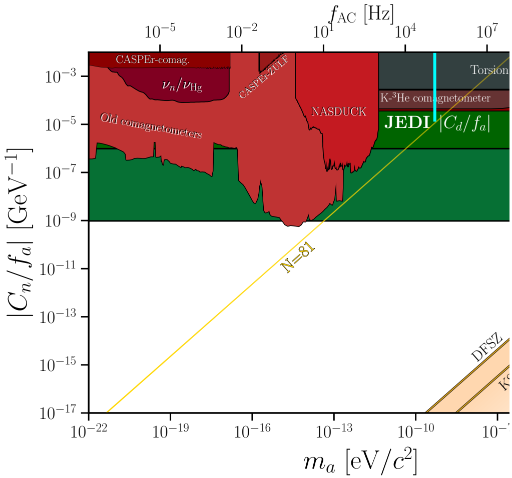
Axion Wind Effect: Coupling to Nucleons C_N/f_a



- storage ring experiments particularly sensitive to axion wind effect ($\beta = \mathcal{O}(1)$)
- JEDI result: engineering run (few days of data taking)

(Jülich Electric Diploe moment Investigations)

Axion Wind Effect: Coupling to Nucleons C_N/f_a



2023 PDG:

10 *90. Axions and Other Similar Particles*

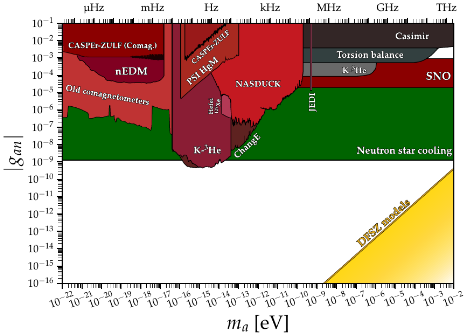


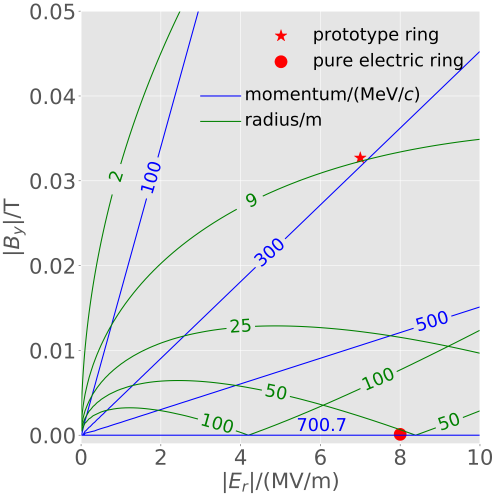
Figure 90.3: Exclusion plot for ALP-neutron coupling as described in the text. Figure courtesy of Ciaran O'Hare [61], includes data from refs. [40, 42, 206, 245–255]. The hadronic axion model prediction is given in Eq. (90.11) with vanishing quark couplings, while the DFSZ model prediction depends on $\tan\beta$ 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.

Where to go from here?

- Use combination of $\vec{E}$ and $\vec{B}$ bending field to reach frozen spin condition $\vec{\Omega}_{\mathrm{MDM}} = 0$ to perform EDM measurement
- Use counter rotating beams to better control systematics
- for axion searches explore wider mass range by varying $\vec{\Omega}_{\mathrm{MDM}}$

Construct a dedicated storage ring!

Momentum and ring radius for proton in frozen spin condition

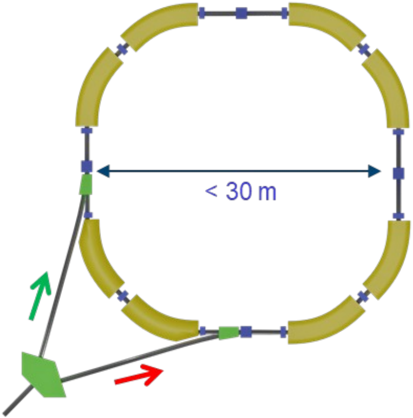


Two options:

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

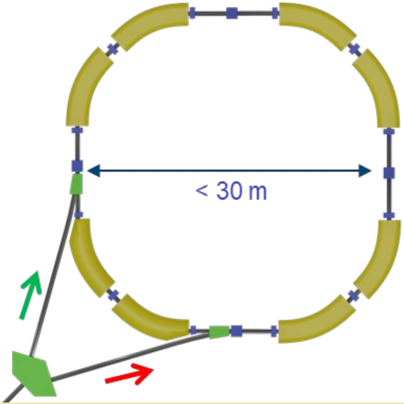
⋆ combined prototype ring:
p = 300MeV, bending radius≈ 9 m at E=7 MV/m

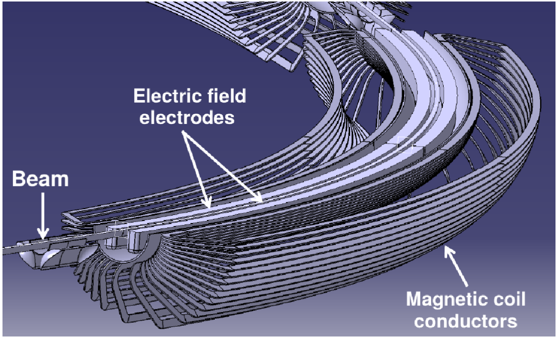
Prototype Ring: Lattice & Bending Element



- 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

Prototype Ring: Lattice & Bending Element





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

Summary I

1. What are the important / primary scientific questions of the field?
   CP-violation beyond SM, matter-antimatter asymmetry, dark matter
2. Which experimental options exist to answer them (completely, partially,?) and when?
   high precison storage ring, 5-10 years
3. For proposed projects: Are scientifically important results guaranteed, likely or possible?
   first direct measurement of proton EDM (10^{-26} $e$cm, similar to neutron sensitivity), measurement of axion/ALP couplings
4. Which secondary topics are covered by the project and what are its chances for success?
   Primary goal: EDM-measurement, secondary goal: search for axion/ALPs

Summary II

5. Estimate of the time scales, costs (invest) and structures (collaboration size and international composition). Which risks exist?
   JEDI collaboration $\approx$ 100 members in addition CERN, MPI Heidelberg, GSI,
   costs: 20MEuros for prototype ring (100m circumference)
   Risks: Find host institution
6. Which competing projects exist world-wide for the physics question, taking also realistic schedules and progress into account?
   Proposed project at Brookhaven National Laboratory (ring in existing AGS tunnel) to build pure electrostatic ring ($>$ 500 m circumference)
7. Where is the specific German interest? Do special strengths of German groups play a role? Are there enough interested groups/people for a meaningful contribution?
   Sustain Germany´s strong role in accelerator and sub-nuclear physics, Exploit experience of communnity (i.p. IKP at FZJ) in spin physics with storage rings

Summary III

8. Will the participation create synergies and international visibility? How does the required funding fit to the German funding structures (which funding line, volume)?
   Synergies: hadron, accelerator, particle and astroparticle physics
   Visibility: any EDM/DM result will have a big impact
   Funding: must be international and will depend on host lab,
9. Where could the project be realized? Funding agencies of other countries look much more after attracting some projects to their countries. This has different advantages including positive economic effects for the region, better contributions due to ease of access (it is much easier to contribute and make an impact close-by compared to far away) to visibility and prestige for the country in general and via awards/prizes.
   Everywhere where (polarized) hadron beams are/will be available (CERN/GSI)

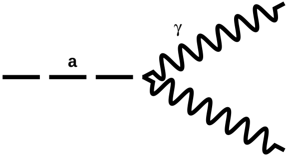
Summary IV

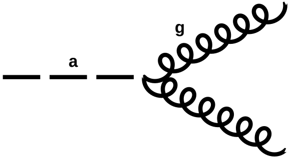
10. Are there special opportunities which should be realized since others have so far paid little or no attention to emerging topics?
    complementary access to axion/ALP searches

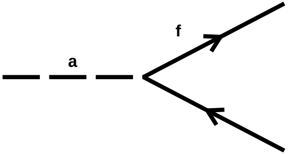
Extra Slides

Axion Coupling

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







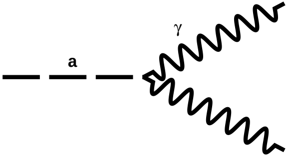
oscillating Electric Dipole Moment (oEDM)

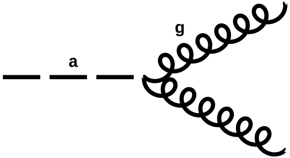
axion wind term

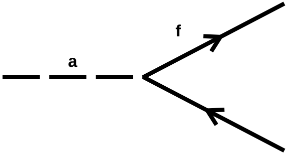
For low axion masses, if axions saturate dark matter they can be described by classical field: $a(t) = a_0 \cos(\omega_a t + \varphi_a)\,, \quad m_a c^2 = \hbar\omega_a\,, \quad \text{Coupling} \propto \frac{1}{f_a} \propto m_a$

Axion Coupling

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







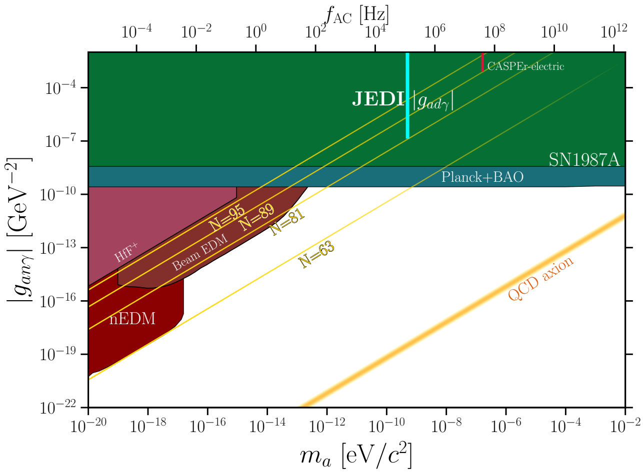
oscillating
Electric Dipole Moment (oEDM)

axion wind term

studied by many experiments

accessible in storage ring experiments with spin polarized beams

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

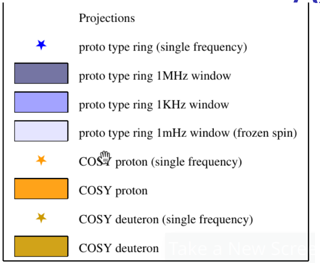
How to Explore a Wider Mass Range m_a

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 for COSY and a prototype storage ring for EDM measurements