Axion Search Possibilities in Storage Rings

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The Strong CP Problem

- The θ_{QCD} parameter in Quantum Chromodynamics (QCD) is expected to have a value between 0 and 2π.
- Experimentally, θ_{QCD} is found to be less than 10^{-10}.
- Its value being so small is coined as the **Strong CP Problem**.

Solution: The Peccei-Quinn Mechanism and Axions

- **Peccei-Quinn Mechanism** proposes the existence of a new symmetry to explain the smallness of θ_{QCD} .
- This symmetry introduces a new particle called the **axion**.
- The axion field dynamically adjusts θ_{QCD} to a very small value, resolving the Strong CP Problem.

Axion Oscillations and θ_{QCD}

- Axion oscillations minimize the θ_{QCD} .
- The frequency of these oscillations is proportional to the axion mass:

  $$f_a = \frac{m_a c^2}{h},$$

  where m_a is the axion mass.
- θ_{QCD} , (hence the EDM) has some oscillating component at the axion frequency
- If θ_{QCD} is not perfectly cancelled, there remains a DC component as well.

Axion Search with Spin Experiments

- Searching axions through **strong interactions** was proposed some 10-15 years ago.
- Original proposals were focusing on Torsion Pendulum, Atomic Magnetometers, Atom Interferometry, etc.
- PRD 84, 055013 (2011), PRD 88, 035023 (2013), PRD 97, 055006 (2018).
- The biggest benefit of the spin experiments is the access to very low and very high frequencies.

Electric Dipole Moments (EDMs) and θ_{QCD}

- **EDMs** are a measure of the charge distribution within a particle, aligned with its spin.
- The existence of a nonzero EDM signals CP violation, which is crucial in understanding the matter-antimatter asymmetry in the universe.

$$H = -\vec{d} \cdot \vec{E}$$

- In Standard Model, the θ_{QCD} contributes to the EDM of particles.
- Experimental limit for θ_{QCD} is set by the Neutron EDM experiment:

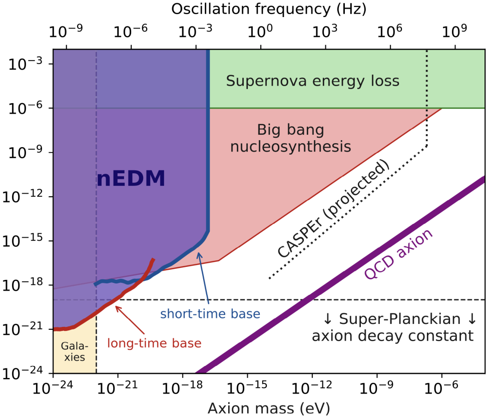
$$d_n = 3.1 \times 10^{-16}\ \theta_{\text{QCD}}\ [e \cdot \text{cm}] \rightarrow \theta_{\text{QCD}} < 10^{-10}.$$

- In the context of axions, EDMs can have both a static and a time-varying component:

$$d = d_{\text{DC}} + d_{\text{AC}} \cos(m_a t + \phi_a).$$

Axion Search with EDM Experiments

- EDM experiments in storage rings fit well for this task.
- Data from the Neutron EDM experiments were analyzed to cover some low frequency region
- PRX 7, 041034 (2017).



Spin in Storage Rings

- Polarized beams have been studied for a long time in storage rings.
- The spin precession is defined by T-BMT (Thomas-Bargmann-Michel-Telegdi) equations:

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

Horizontal $(g-2)$ spin component

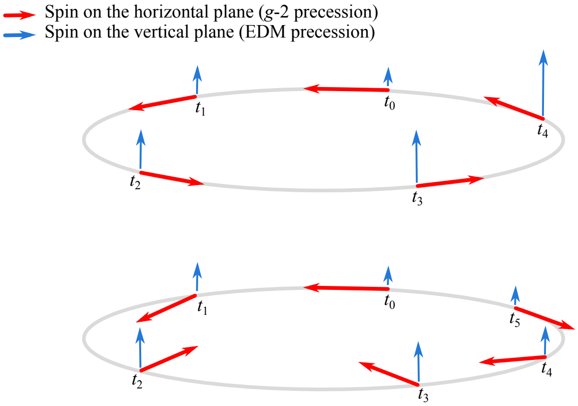
$$\omega_{sy} = -\frac{q}{m}\left[\left(G+\frac{1}{\gamma}\right)B_y - \left(G+\frac{1}{\gamma+1}\right)\frac{\beta E_x}{c}\right]$$

Vertical (EDM-induced) spin component

$$\omega_{sx} = -\frac{q}{2m}\eta\left(\frac{E_x}{c} - \beta B_y\right).$$

Horizontal and Vertical Spin Precession

$$\omega_{sy} = -\frac{q}{m}\left[\left(G+\frac{1}{\gamma}\right)B_y - \left(G+\frac{1}{\gamma+1}\right)\frac{\beta E_x}{c}\right] \;\; ; \;\; \omega_{sx} = -\frac{q}{2m}\eta\left(\frac{E_x}{c} - \beta B_y\right).$$



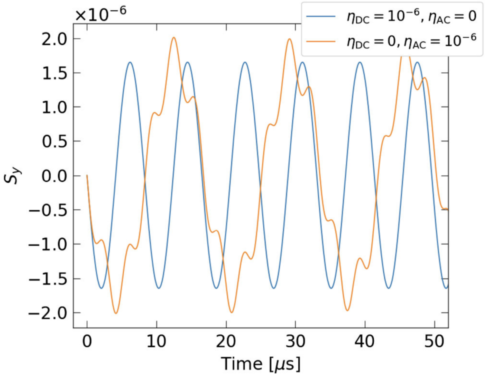
The vertical component is orders of magnitude smaller than horizontal.

EDM-Induced Spin Precession

- Vertical spin precession is influenced by the presence of an EDM:

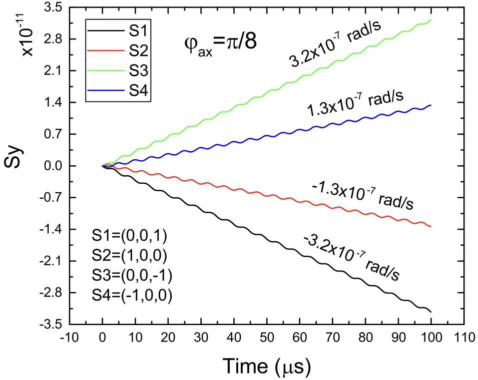
$$\omega_{sx} = -\frac{q}{2m}\eta\left(\frac{E_x}{c} - \beta B_y\right) \quad ; \quad \frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

  where η is the electric dipole moment coefficient.
- Plot from PRD 104, 096006 (2021).



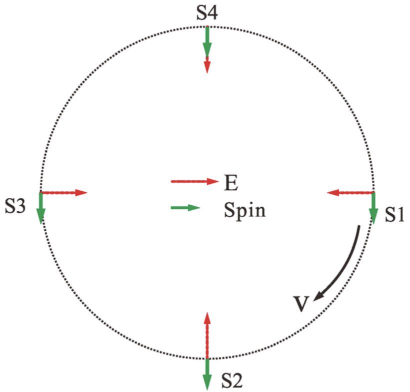
EDM-Induced Spin Precession

- If an axion-induced EDM exists at $g-2$ frequency, the resonance makes the vertical spin component grow.
- Growing vertical spin component indicates axion at $g-2$ frequency.
- Plot from PRD 104, 096006 (2021).



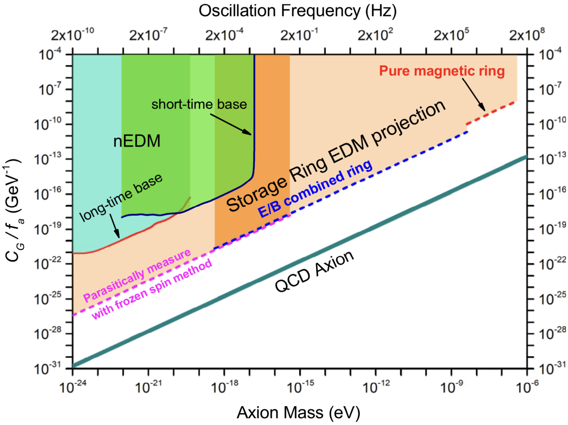
Matching the Axion Phase

- To avoid missing a potential axion signal, multiple particle bunches sholud be used, each with different initial spin polarizations.
- This approach ensures that if a resonance occurs, it will be detected in at least two of the bunches.
- The polarization of each bunch is perpendicular to the others.



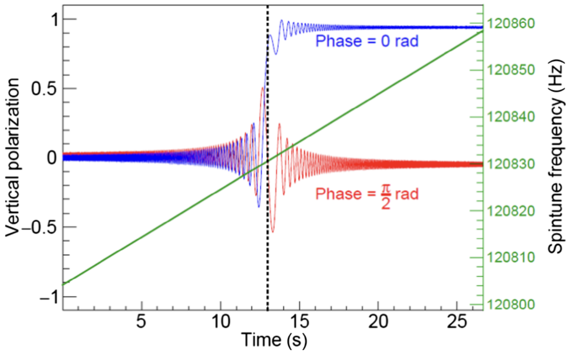
Axion Search with Proton EDM Experiment

- An experiment at the proposed Proton EDM ring can cover a wide range of axion masses.
- This includes both low and high-frequencies, which are not available especially for cavity experiments.
- Every 3 orders of magnitude take roughly 2 years.



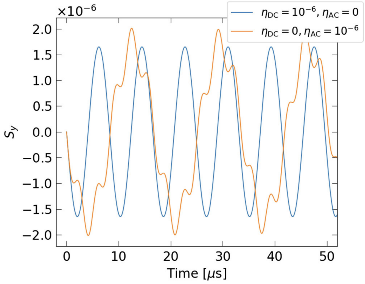
Axion Search at COSY Storage Ring

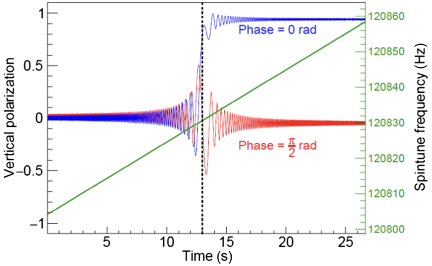
- The JEDI Collaboration conducted the first axion search in a storage ring at COSY.
- By gradually sweeping the g-2 frequency, the experiment aimed to find a resonance with the axion field.
- A jump in the vertical polarization component during the run indicates a potential axion signal.



Proof-of-Principle Test at COSY Storage Ring

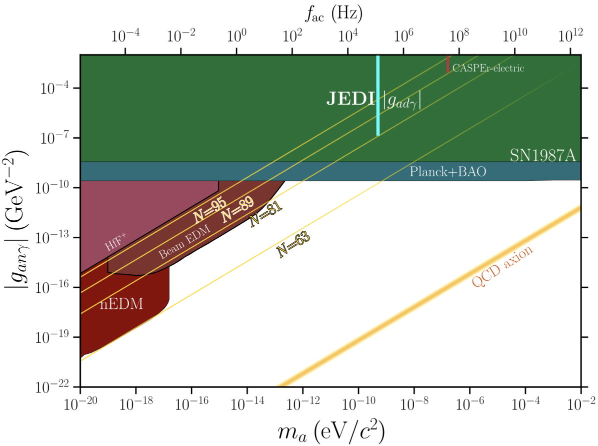
- They had four bunches with almost perpendicular polarizations
- Wien Filters (WF) provided an oscillating horizontal magnetic field at a specific frequency (f_{WF}).
- This field oscillated the vertical spin component, mimicking the axion signal.
- They observed a jump as expected.





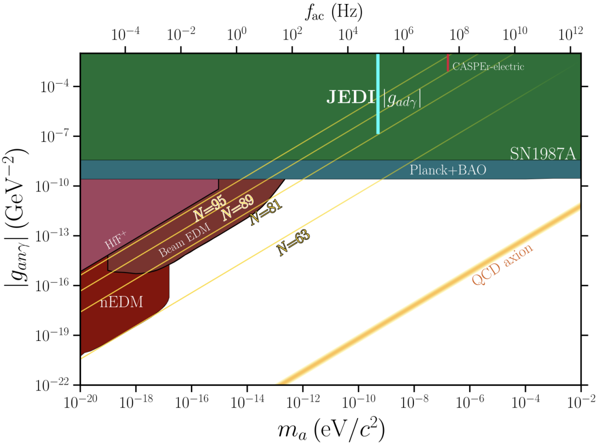
Axion Search at COSY Storage Ring

- Then, they scanned a range of frequencies to search axion signal.
- Data taking took 4 days.
- Eventually, they ruled out the region with cyan color.
- The search was done at around 120 kHz (0.5 neVs)
- PRX 13, 031004 (2023).



Axion Search at COSY Storage Ring

- Perhaps the biggest difficulty with the COSY Experiment was sweeping the $g-2$ frequency.
- Because of possible beam and spin instabilities.

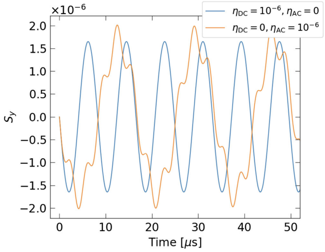


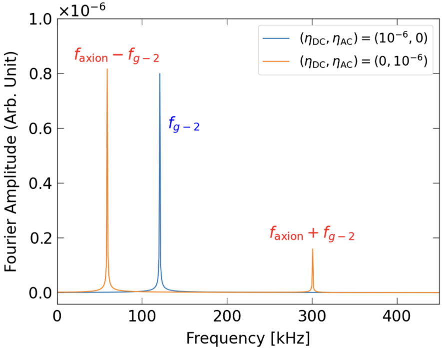
Wien Filter

- A Wien filter is a device that can simultaneously apply electric and magnetic fields perpendicular to each other.
- It allows tuning the magnetic field by cancelling the Lorentz force, which could cause instabilities otherwise.
- More than mimicking an axion signal can be done by this setup.

Off-Resonance Axion Signal and Sidebands

- Off-resonance axion signal doesn't resonate, but modulates the $g-2$ precession.



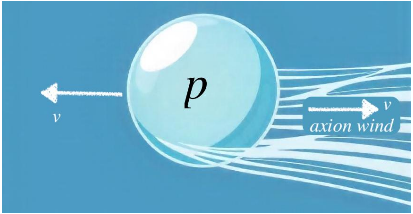


Axion Search with Wien Filters

- A WF can be used to resonate those sidebands.
- The rest of the proposed experiment is similar to what was done at COSY.
- The sensitivity is similar.
- But the systematics are quite easier to handle.
- PRD 104, 096006 (2021).

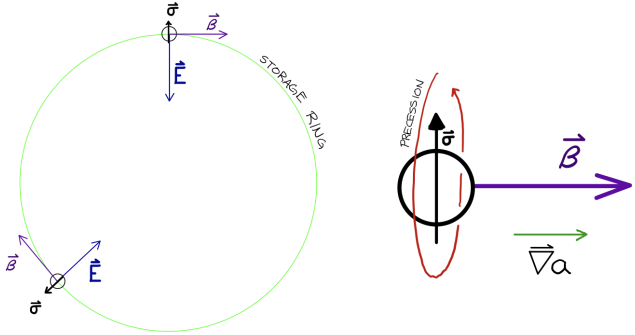
Inside Axion Wind

- This method does not require θ_{QCD} coupling.
- An axion wind contributes to the Hamiltonian with a term: $H = -g_{aNN}\vec{\nabla}a \cdot \vec{s}$
- Gradient of an axion wind behaves like a pseudo magnetic field.
- So, the spin precesses around the magnetic field (like $g-2$ precession).



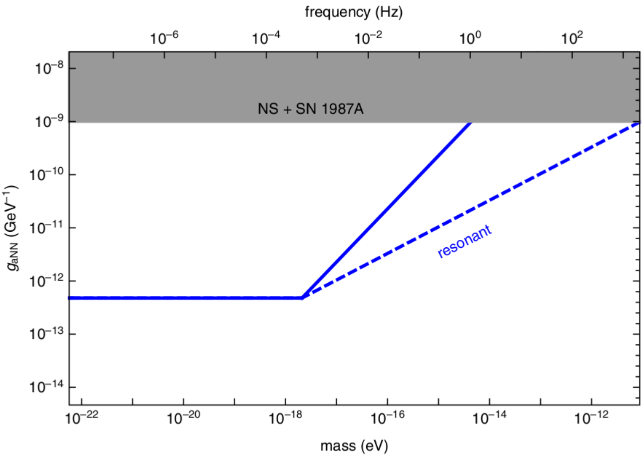
Inside Axion Wind

- The spin precesses around the magnetic field.
- It precesses larger as speed increases.



Inside Axion Wind

- PRD 97, 055006 (2018).



Summary

- Storage ring spin experiments allow axion measurement in a wide frequency range.
- They are particularly useful if axion signal is found at an experiment. The storage ring search can be made at that frequency to see if the axion has gluon coupling.
- The storage ring axion search is typically based on resonating the beam polarization at
  - $g - 2$ frequency or
  - its sidebands with axion frequency modulation
- Small axion oscillations can be handled by EDM measurements with frozen spin method (with no $g - 2$ oscillation).
- DC-like axion oscillations can be handled by radially polarized beams (with no $g - 2$ oscillation).