Towards experiments with polarized beams and targets at the GSI/FAIR storage rings

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History

- Scientists at IKP (Institut für Kernphysik) at Forschungszentrum Jülich have large experience in experiments with polarized hadron beams and targets
- Forschungszentrum Jülich decided to stop research in this area.
- There is a TransFAIR process ongoing to integrate IKP members into GSI/FAIR.
- A common LOI
  “**Towards experiments with polarized beams and targets at the GSI/FAIR storage ring**”
  has been submitted to GPAC in July 2022

Letter of Intent: Towards experiments with polarized beams and targets at the GSI/FAIR storage rings

A. Bondarev[1,2], R. Engels[3], S. Fritzsche[1,2,4], R. Grisenti[2,5], A. Gumberidze[2], V. Hejny[3], P.-M. Hillenbrand[1,2], A. Kacharava[3], T. Krings[3], A. Lehrach[3], M. Lestinsky[2], Yu. A. Litvinov[2], B. Lorentz[2], A. Maiorova[1,2], F. Maas[6,7], W. Middents[1,4], A. Nass[3], T. Over[1,4], P. Pfäfflein[1,2,4], J. Pretz[*3], N. Petridis[2], J. Ritman[2,13,3], F. Rathmann[3], S. Schippers[8,9], R. Schuch[1,10], M. Steck[2], Th. Stöhlker[†1,2,4], U. Spillmann[2], A. Surzhykov[11,12], G. Weber[1,2], and B. Zhu[1,4]

Polarization Effects

Unpolarized cross section:

$$\sigma_{tot} = \sigma_o$$

Polarization Effects

Polarized cross section:

$$
\begin{aligned}
\sigma_{tot} &= \sigma_o + \sigma_{TT}\left[(\mathbf{P^d}\cdot\mathbf{P^p}) - (\mathbf{P^d}\cdot\mathbf{k})(\mathbf{P^p}\cdot\mathbf{k})\right] \\
&+ \sigma_{LL}(\mathbf{P^d}\cdot\mathbf{k})(\mathbf{P^p}\cdot\mathbf{k}) + \sigma_T T_{mn}k_m k_n \\
&+ \sigma^p_{PV}(\mathbf{P^p}\cdot\mathbf{k}) + \sigma^d_{PV}(\mathbf{P^d}\cdot\mathbf{k}) \\
&+ \sigma^T_{PV}(\mathbf{P^p}\cdot\mathbf{k})T_{mn}k_m k_n \\
&+ \sigma^T_{TVPV}\left(\mathbf{k}\cdot(\mathbf{P^p}\cdot\mathbf{P^d})\right) \\
&+ \sigma^T_{TVPC}k_m T_{mn}\epsilon_{nlr}P^p_l k_r
\end{aligned}
$$

$\mathbf{P^p}$: proton polarization, $\mathbf{P^d}$: deuteron vector polarization, $\mathbf{T}$: deuteron tensor polarization, $\mathbf{k}$: unit vector along collision axis

Many additional observables, some test C,P, and/or T symmetry.

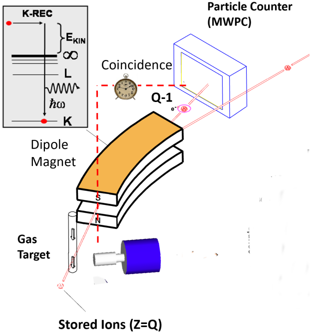
N. Nikolaev et al., Phys.Lett.B 811 (2020) 135983

Outline (Content of Proposal)

- Study spin transfer in Radiative Electron Capture (REC)
  with the ultimate goal is to produce beams of spin-polarized heavy nuclei
- Search for axion/axion like particles
- Search for a time reversal violating/parity conserving asymmetry

Radiative Electron Capture (REC)

Radiative Electron Capture



Radiative Electron Capture (REC):

$$Z^{Q+} + \vec{e}^{-} \rightarrow Z^{*(Q-1)+} \rightarrow Z^{(Q-1)+} + \vec{\gamma}$$

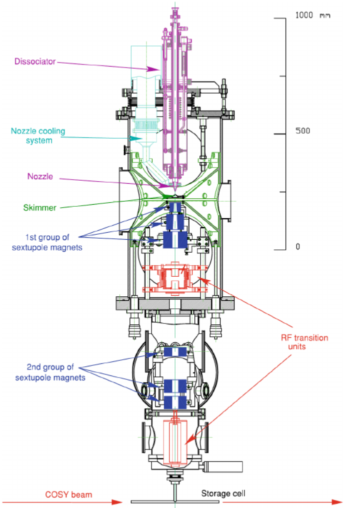
Plans:

1. Use Anke from FZJ polarized target to provide polarized electrons
2. measure photon polarization for U^{91+} at 400 MeV/u
3. Study spin polarization build-up, Breed U^{91+} via REC
4. spin transfer to nuclei (e.g. $^{209}Bi^{82+}$) with large magnetic moment (and HFS of 4 eV)
5. **tool to generate polarized heavy nuclei**

Polarized target

- about 10^{17} atoms per second, corresponding to 10^{12} atoms/cm^2
- with suitable cell 10^{14} atoms/cm^2 can be reached
- nuclear/electron polarisation of H or D reach typically 90%

Atomic beam source used at ANKE $\rightarrow$ experiment at COSY as polarized target



Max Mikirtychyants et al., Nucl. Instr. Meth. A 721, p. 83-89, (2013)
DOI: 10.1016/j.nima.2013.03.043

Axion/ALP searches

Axions/Axion Like Particles (ALPs)

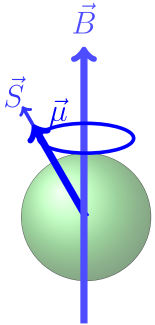
- hypothetical elementary particle postulated by Peccei,Quinn,Wilczek,Weinberg to resolve the strong CP problem
- axion are also dark matter candidates
- axion like particles (ALP): similar properties as axions, (but ALPs don't solve the strong QCD problem)
- huge experimental effort to search for axion/ALPs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

Spin Motion in storage ring

with respect to momentum vector in magnetic field

$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{\mathrm{MDM}} \qquad\qquad) \times \vec{S}$$

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



B	magnetic field
G	magnetic anomaly
g	g-factor
μ	magnetic moment
S	spin
q, m	mass, charge
d	Electric Dipole Moment (EDM)

Spin Motion in storage ring

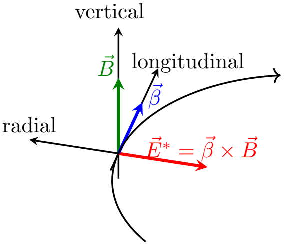
with respect to momentum vector in magnetic field

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

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

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

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



axion field: $a(t) = a_0 cos(\omega_a t + \phi_0)$ $\quad d = d_{\mathrm{DC}} + d_{\mathrm{AC}} \cos(\omega_a t + \phi_0)$

$\hbar\omega_a = m_a c^2$ $\quad d_{AC} = a_0 g_{ad\gamma}, \quad g_{ad\gamma}$: ALP-EDM coupling

Spin Motion in storage ring

with respect to momentum vector in magnetic field

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

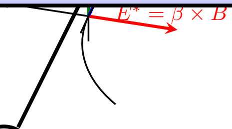
$$\vec{\Omega}_{\rm MDM} = -\frac{q}{m}\, G\vec{B}$$

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

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

Permanent EDM d_{DC}:

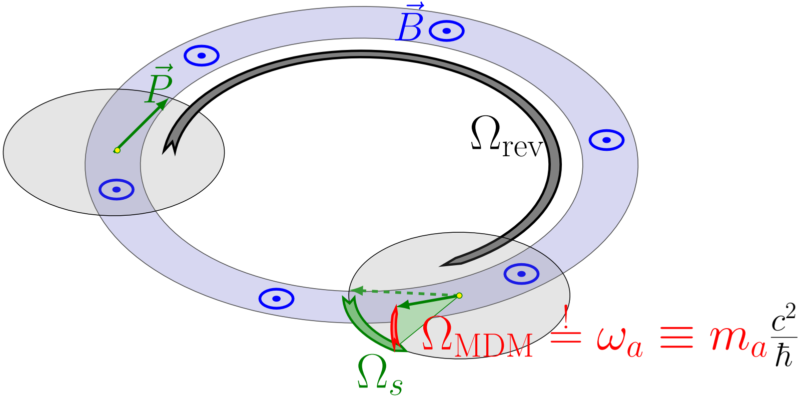
- JEDI collaboration:
  activities at COSY/FZJ
- EU proposal PRESTO:
  design of a dedicated storage ring



axion field: $a(t) = a_0 cos(\omega_a t + \phi_0)$ $\quad d = d_{\rm DC} + d_{\rm AC}\cos(\omega_a t + \phi_0)$

$\hbar\omega_a = m_a c^2$ $\quad d_{AC} = a_0 g_{ad\gamma}$, $\quad g_{ad\gamma}$: ALP-EDM coupling

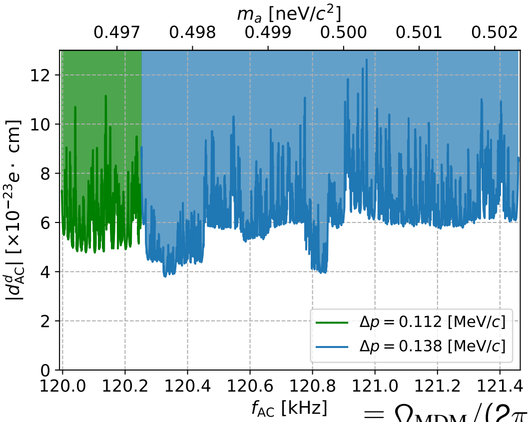
Axion Experiment at storage rings



Principle of experiment

- store polarized hadrons
- maintain precession in horizontal plane
- if $m_a c^2 = \Omega_{\mathrm{MDM}} \hbar$, polarization will turn out of the horizontal plane, resulting in a vertical polarization component
- Vertical polarization can be measured using a polarimeter (in case of deuteron: deuteron carbon scattering)
- AC measurement (i.e. systematics are under control)
- axion wind effect enhanced in storage rings ($v_{\mathrm{particle}} \approx c$)
- one can either scan a certain mass range by scanning Ω_{MDM} or measure at a fixed frequency to look for ALP at a specific mass.

Axion Analysis: d_{AC}, results from COSY

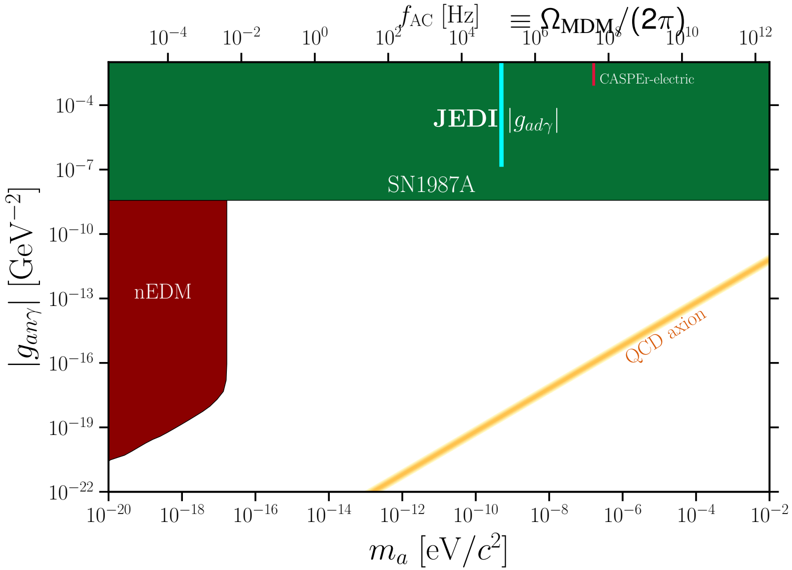


$\equiv \Omega_{\mathrm{MDM}}/(2\pi)$

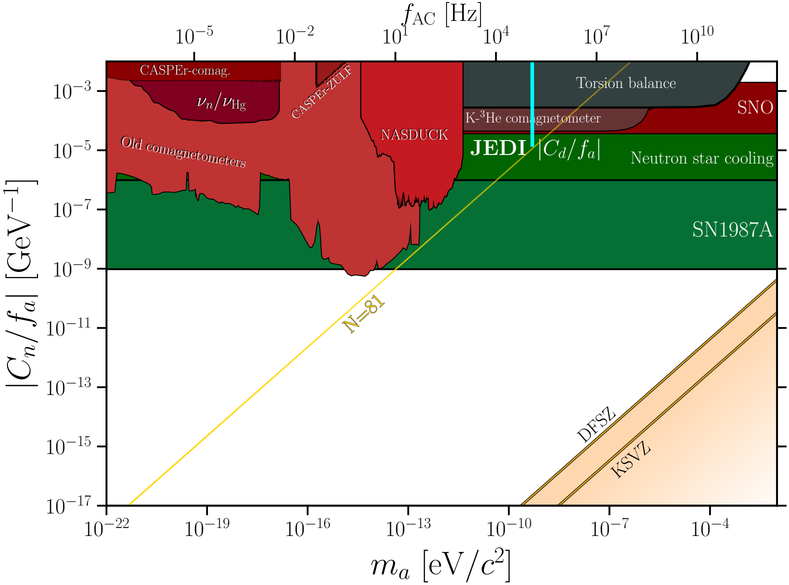
- a few days of beam time
- $f_{AC} = \frac{1}{2\pi}\frac{m_a c^2}{\hbar} = \gamma G f_{\mathrm{rev}}$

https://arxiv.org/abs/2208.07293 submitted to PRX

Axion Analysis: axion anomalous coupling to gluons $g_{aN\gamma}$



Axion Wind effect: coupling to nucleons C_N/f_a



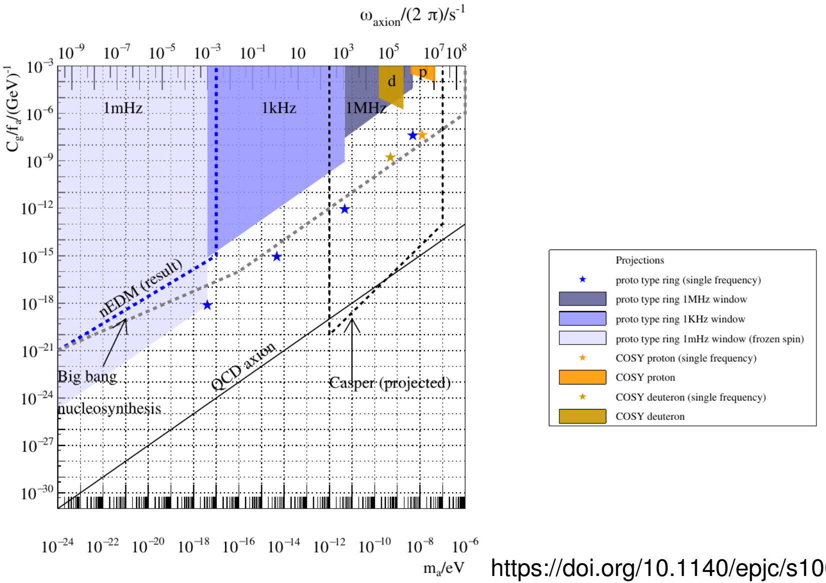
How to explore a wider mass range m_a

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

1. modify beam energy (changes γ, Ω_{rev})
2. use different nuclei (changes G)
3. Use additional electric field

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

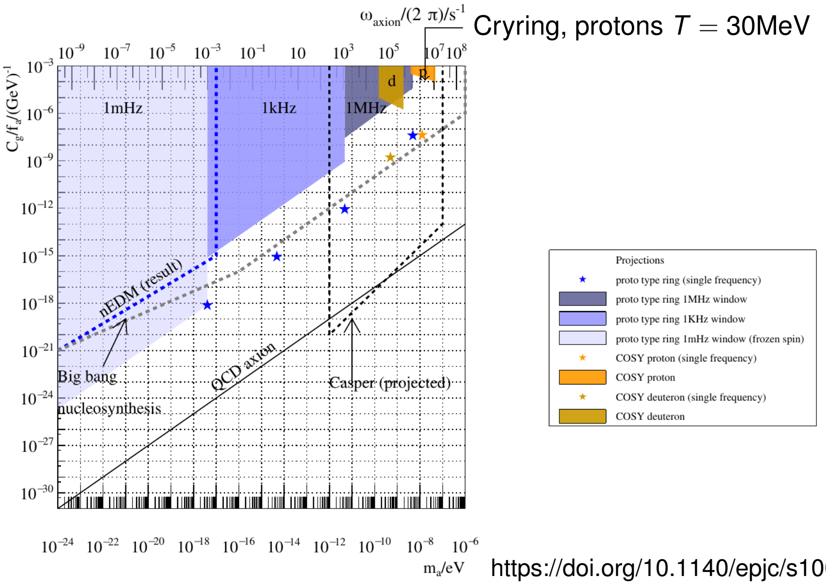
Axion Searches at storage rings



https://doi.org/10.1140/epjc/s10052-020-7664-9

Axion Searches at storage rings

Cryring, protons $T = 30\text{MeV}$

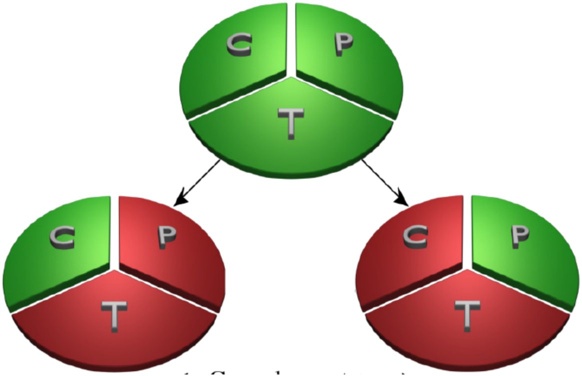


https://doi.org/10.1140/epjc/s10052-020-7664-9

Measurement of Parity even/Time reversal odd asymmetry

Polarized proton-deuteron scattering

Search for a **time reversal violating** and **parity conserving** asymmetry in polarized proton-deuteron scattering



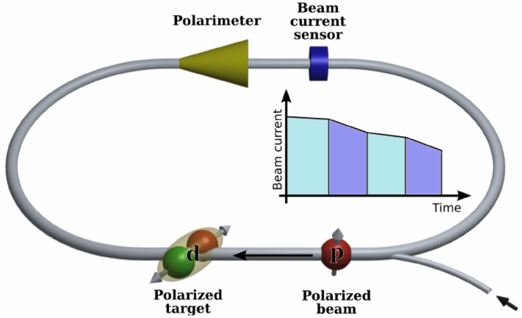
Electric Dipole Moments (EDM)

polarized proton-deuteron scattering

axion searches

Polarized proton-deuteron scattering

polarized proton beam, tensor polarized deuteron target



$$\sigma_{tot} = \sigma_{Y,XZ} + \sigma_{loss} = \sigma_0 \left(1 + P_Y^{p\text{beam}} P_{XY}^{d\text{target}} A_{Y,XZ}\right) + \sigma_{loss} \,, \qquad \left(A_{Y,XZ} \propto \frac{\sigma^T_{TVPC}}{\sigma_0}\right)$$

Giuseppe Ciullo1, Paolo Lenisa, JPS Conf. Proc. 35, 011012 (2021), https://doi.org/10.7566/JPSCP.35.011012

Summary & Outlook

- Storage ring experiments with **polarized** beams/targets offer a wealth of possibilities
- LOI to G-PAC submitted:
  "*G-PAC statement: G-PAC recognises the opportunities that polarised beams would open at GSI/FAIR and encourages the collaboration to submit a proposal*"
- Further investigations (beam energies, error estimates, installation of sources and targets, beam instrumentation) for experiments at ESR/Cryring still needed (PhD student, Daoning Gu, starts 01.03.2023)