J.D. Bjorken (1987, with reference to spin crisis): "Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might well ban such measurements altogether out of self-protection".

Decoherence of Tensor Polarization

N.N. Nkolaev

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SPRINT Meeting, LHEP, 04.03.2026

In collaboration with

F. Rathmann (BNL), A. Silenko (JINR BLTP) and Yu . Uzikov (JINR DLNP)

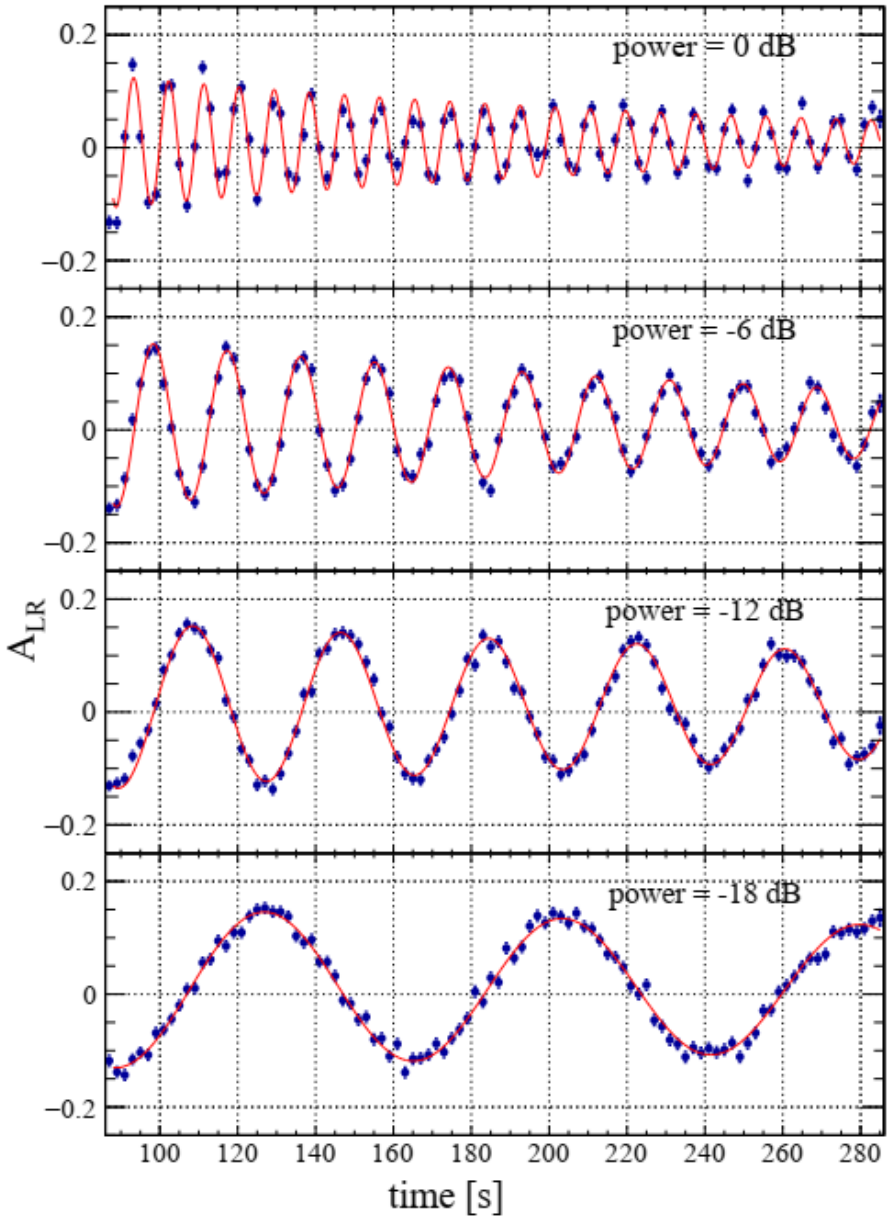
Interest in Tensor Polarization of Spin-1 Deuterons

- Pioneering studies at LHEP have uncovered puzzling tensor asymmetries: is the deuteron more than a pn bound state?
- SPD@NICA: gluon tensor structure function A. Arbuzov *et al.*, (Review 2021)
- JEDI (and Sitnik et. Al (2002)) driven interest in oscillating polarizations
- SPD&NICA and NuclotronM : T-violation in pd, dd and millistrong CP-violation BSM.
  L. Okun, T.D. Lee & L. Wolfenstein, J. Prentki & M. Veltman (1965); Y.uN. Uzikojv et al.
- Parity violation with polarized protons and deuterons I.Koop et al (2021)
- Baryshevsky: a background from tensor asymmetry to the signal of EDM?
- Baryshevsky/Silenko: tensor polarizibilitiy of deuterons
- Variable tensor polarization at flattop is a must for extraction of tensor asymmetries
- Good news for NICA: rf flipped spin will be preserved for several hour collision time

Proton spin lifetime in COSY: spinoff from spin filtering machine studies

C. Weidemann et al., Phys. Rev. ST Accelerators and Beams, 18, 020101 (2015)

- 49.3 MeV protons in COSY
- Without spin-flips the vertical polarization lifetime (2.7 +/- 0.5) 10^5 s
- 99 spin flips during 300 s (0.15 Hz)
- Flipping polarization lifetime 240 s.
- Polarization loss by spin decoherence in the horizontal plane? Or is the spin-flip per se a culprit?
- JEDI: depolarization of the idle precession of the porizontal polarization. Tune sextupole families to zero chromaticity → spin coherence time up to 1500 s. (talk by Yu.V. Senichev)



Spin decoherence: Spin-off from the JEDI axion search

S.Karanth et a., Phys. Rev. X 13, 031004 (2023)

- Polarization damping stronger for higher spin-flip frequency & larger spin-flip phase $x=2\pi f_{sf\backslash}\, t$
- First evidence for a **prominent** synchrotron oscillation driven depolarization: theory in N.Nikolaev et al. *PRAB 27* (2024) 111002.
- Avergge over ensemble → Non-exponential attenuation and nonlinear spin-flip phase walk

$$D(x) = \frac{1}{\sqrt{1+Q_{\rm sy}^2 x^2}} \qquad Q_{\rm sy} = \frac{1}{2}(K+G\gamma)^2\sigma_{\rm sy}^2$$

$$\phi(x) = \arctan(Q_{\rm sy}x)\,.$$

$\sigma_{\rm sy} \ll 1$ is the rms angular length of a bunch

- JEDI data analysis is in progress

Spin envelopes in spin flip (y=vertical, x=radial, z= tangential)

- Idle precession: $\vec{S}(n) = \mathbf{R}_s(n\theta_s)\vec{p}(n)$ $\mathbf{R}_s(\theta_s) = \begin{pmatrix} \cos\theta_s & 0 & \sin\theta_s \\ 0 & 1 & 0 \\ -\sin\theta_s & 0 & \cos\theta_s \end{pmatrix}$

$\theta_s = 2\pi\nu_s$ $\nu_s = 2\pi G\gamma,$

- Envelope: $\vec{p}(n) = \mathbf{E}(x)\vec{p}(0)$ $\mathbf{E}(x) = \begin{pmatrix} \cos x & \sin x & 0 \\ -\sin x & \cos x & 0 \\ 0 & 0 & 1 \end{pmatrix}$

Spin flipper is RF solenoid

- Spin tensor $\mathbf{T}_{mn} = \frac{1}{2}(S_m S_n + S_n S_m - \frac{2}{3}\delta_{mn}\vec{S}^2)$ 5 independent elements --- 5 dimensions ?

- Tensor envelope $\mathbf{t}(n) = \mathbf{R}_s^{-1}(n\theta_s)\mathbf{T}(n)\mathbf{R}_s(n\theta_s)$

- Tensor envelope evolution $\mathbf{t}(n) = \mathbf{E}(x)\mathbf{t}(0)\mathbf{E}^T(x)$ via 3x3 matrices, no need to solve secular equaation in 5D space

Silenko 2015, Nikolaev, Rathmann, Silenko, Uzikov 2020

Evolution of tensor polarization: reference particle

$$\frac{1}{2}(t_{xx}(n) - t_{yy}\ (n)) =$$

$$= \frac{1}{2}(t_{xx}(0) - t_{yy}(0))\cos 2x + t_{xy}(0)\sin 2x\ ,$$

$$t_{xy}\ (n) = -\frac{1}{2}(t_{xx}(0) - t_{yy}(0))\sin 2x + t_{xy}(0)\cos 2x$$

Vector in vertical XY plane, rotates with double spin-flip frequency

$$t_{xz}(n) = t_{xz}(0)\cos x + t_{yz}(0)\sin x\ ,$$

$$t_{yz}(n) = -t_{xz}(0)\sin x + t_{yz}(0)\cos x\ ,$$

$$t_{zz}(n) = t_{zz}(0)\ ,$$

Vector in vertical XY plane, rotates with the spin-flip frequency

We found eigenfunctions without ever troubling with a secular equation for 5x5 matrix

Depolarization from averaging over ensemble

- Spin tune $\nu_{\rm sf}(\xi) = \nu_{\rm sf} J_0(2\xi\sqrt{Q_{\rm sy}})$

- Spin-flip phase $x \to x(Q_{\rm sy}\xi) = J_0(2\xi\sqrt{Q_{\rm sy}}x) \approx (1 - Q_{\rm sy}\xi^2)x$

- Synchrotron amplitude distribution $F(\xi) = 2\xi \exp(-\xi^2)$

$$\frac{1}{2}(t_{\rm xx}(n) - t_{\rm yy}\ (n)) = D(2x)[(\frac{1}{2}(t_{\rm xx}(0) - t_{\rm yy}(0))\cos(2x - \phi(2x)) + t_{\rm xy}(0)\sin(2x - \phi(2x))],,$$

$$t_{\rm xy} = D(2x)[\frac{1}{2}(t_{\rm xx}(0) - t_{\rm yy}(0))\sin(2x - \phi(2x)) + t_{\rm xy}(0)\cos(2x - \phi(2)x))],,$$

$$t_{\rm xz}(n) = D(x)[t_{\rm xz}(0)\cos(x - \phi(x)) + t_{\rm yz}(0)\sin(x - \phi(x))]\,,$$

$$t_{\rm yz}(n) = D(x)[-t_{\rm xz}(0)\sin(x - \phi(x)) + t_{\rm yz}(0)\cos(x - \phi(x))]\,,$$

$$t_{\rm zz}(n) = t_{\rm zz}(0)\,,$$

Boundary condition for stored polarization

$$\langle \vec{S} \rangle = S_{\rm y} \vec{e}_{\rm y}, \quad \langle S_{x,z}(0) \rangle = 0,$$

$$\langle T_{yx}(0) \rangle = \langle T_{yz}(0) \rangle = \langle T_{xz}(0) \rangle = 0\,, \qquad \langle T_{xx}(0) \rangle = T_{zz}(0) \rangle = -\frac{1}{2} \langle T_{yy}(0) \rangle\,.$$

Flipping & depolarizing and spectator components of T

$$\frac{1}{2}[T_{\rm xx}(n) - T_{\rm zz}(n)] = \frac{3}{8}\langle T_{\rm yy}(0)\rangle \cos(2\theta_{\rm s} n) - \frac{3}{8}\langle T_{\rm yy}(0)\rangle Q(2x)\cos(2x - \phi(2x))\cos(2\theta_{\rm s} n)$$

$$T_{\rm xz}(n) = -\frac{3}{8}\langle T_{\rm yy}(0)\rangle \sin(2\theta_{\rm s} n) + \frac{3}{8}\langle T_{\rm yy}(0)\rangle Q(2x)\cos(2x - \phi(2x))\sin(2\theta_{\rm s} n)\,,$$

$$T_{\rm xy}(n) = \frac{3}{4}\langle T_{\rm yy}(0)\rangle Q(2x)\sin(2x - \phi(2x))\cos(\theta_{\rm s} n)\,,$$

$$T_{\rm zy}(n) = -\frac{3}{4}\langle T_{\rm yy}(0)\rangle Q(2x)\sin(2x - \phi(2x))\sin(\theta_{\rm s} n)\,,$$

$$\frac{1}{2}T_{\rm yy}(n) = -\frac{1}{2}[T_{\rm xx}(n) + T_{\rm zz}(n)] = \frac{1}{8}\langle T_{\rm yy}(0)\rangle + \frac{3}{8}\langle T_{\rm yy}(0)\rangle Q(2x)\cos(2x - \phi(2x))],,$$

Пусть безумная идея --- не ругайте сгоряча

((c) В.С. Высоцкий)

Fresh look at the tensor polarimetry

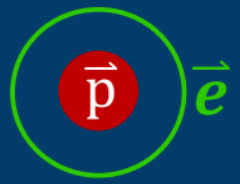
- Fourier signal of time-stamped oscillating polarization is nearly as cood as that of a constant polarization
- CNI polarimetry is indispensable
- Complement the CNI recoil detector by a most primitive forward counters to detect inelastic interaction → high counting rate
- Deuteron is a dumbbell
- The Glauber eclipse effect depends on the orientation of the dumbbell

$$\sigma_{\mathrm{tot}} = \sigma_0(1 + A_{\mathrm{zz}} T_{\mathrm{zz}})$$

- Fourier extraction of the tensor asymmetry
- Reliable Glauber theory of the tensor analyzing power

Spin physics at HIAF

- Nice spin physics at HIAF with polarized target and (un)polarized beams
- Polarized gas target will be used as both proton target and electron target



- Ideas and collaborations are more than welcome!

① pol. e target	**unpol. beams (A, p)**
$Z^{Q+} + \vec{e} \rightarrow Z^{(Q-1)+} + \hbar\omega$	pol. electron capture (atomic physics)
$p\vec{e} \rightarrow pe$	proton EM radii, new boson search
② pol. p target	**unpol. heavy ion beams (C, Ca, Au, …)**
$A\vec{p} \rightarrow Ap$	→ many body structure, nuclear physics
③ heavy target	**pol. d beams**
$\vec{d}A \rightarrow Anp$	EOS → nuclear physics
④ pol. p target	**pol. p beams**
$p\vec{p} \rightarrow pp$, $\vec{p}\vec{p} \rightarrow pp$	A_N, A_{NN} → NN spin dynamics, glueball in t channel, hadron physics
⑤ pol. d target	**pol. p beams**
$\vec{p}\vec{d} \rightarrow pd$	test of time reversal symmetry

Пусть безумная идея --- не ругайте сгоряча (summary)

((c) В.С. Высоцкий)

- Oscullating tensor poilarization is imperative to measure tensor observables
- Polarized deuterons at flattop away off of the spin resonances
- Continuous operation of the rf-solenoid flipper at frequency ($G\gamma$+K)x600 kHz (K=0 is OK)
- Spin-frequency in the ballpark of 0.01 Hz → spins in all bunches flip under time-stamp control
- Spin flip = rotation of the vertical-up spin to the horizontal to the vertical-down and so forth
- Horizontal polarization precesses from the +/-radial to +/- longitudinal
- Time tagged oscillating longitudinal polarization is ideal for the NICA physics
- Short bunches at NICA → weak depolarization of continuously flipping spins over 1-2 hours in the collider mode is an welcome news: don't overlook the JEDI explored potential of the oscillating polarization.

Thank you for your patience!

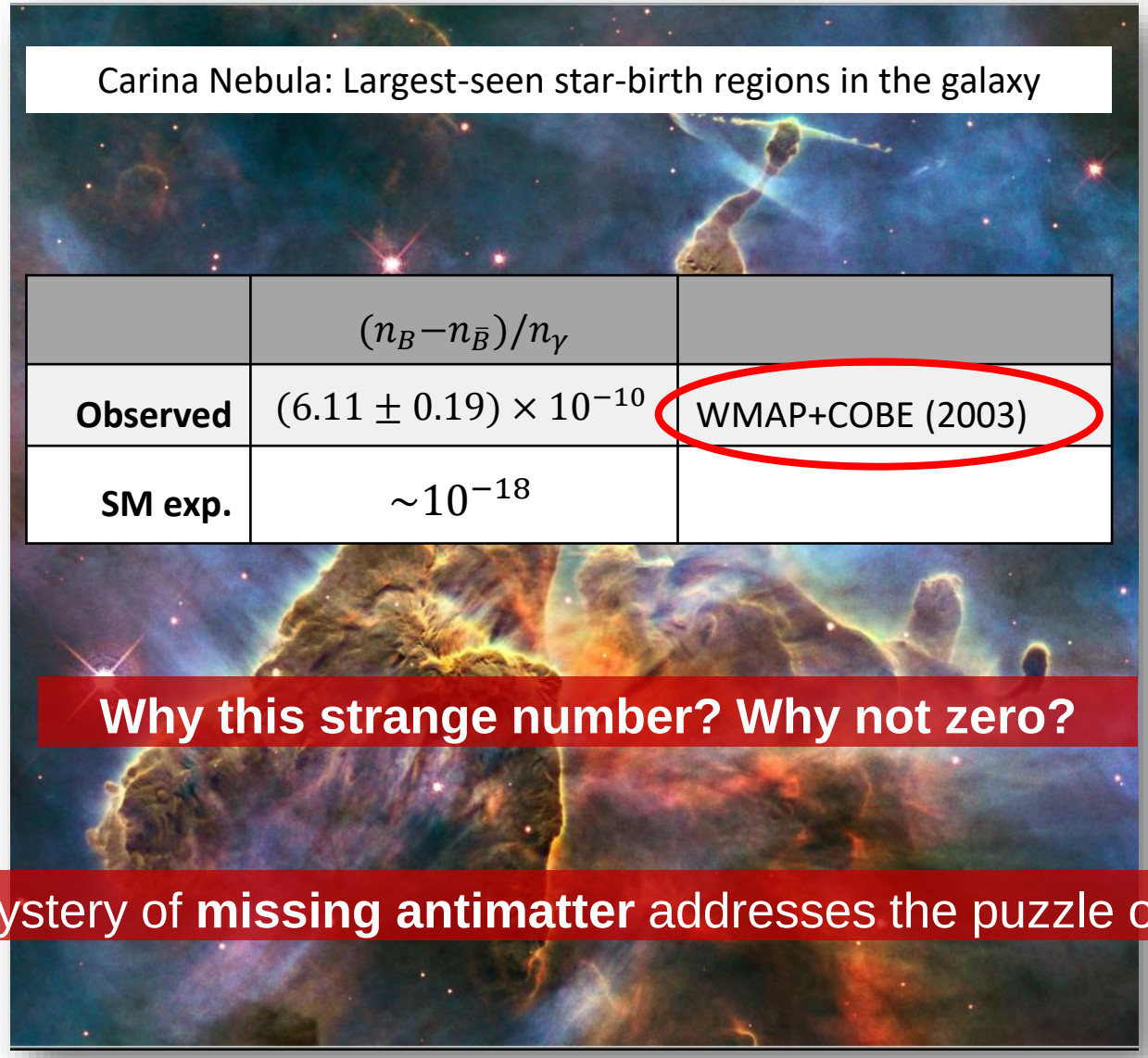
INSPIRE HEP literature (strongly overlapping) listings:

Axions: 10 000+ entries
CP violation: 25 000+
Baryon asymmetry: 6 000+
EDM: 4 000+

A state of the art in precision spin dynamics in storage rings is dominated by more than a decade of JEDI @ COSY

https://collaborations.fz-juelich.de/ikp/jedi/

CP and the observed Baryon Asymmetry in Universe



	$(n_B - n_{\bar{B}})/n_\gamma$	
Observed	$(6.11 \pm 0.19) \times 10^{-10}$	WMAP+COBE (2003)
SM exp.	$\sim 10^{-18}$	

Why this strange number? Why not zero?

Mystery of **missing antimatter** addresses the puzzle of our existence

Sakharov's fundamental criterions

- Baryon number noncoservation
- CP violation
- Nonequilibrium expansion at baryon number generation

All present in the SM, bot it is short of strength

Electric dipole moments (EDMs)

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$ ($\propto \vec{s}$),

- non-relativistic Hamiltonian:

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

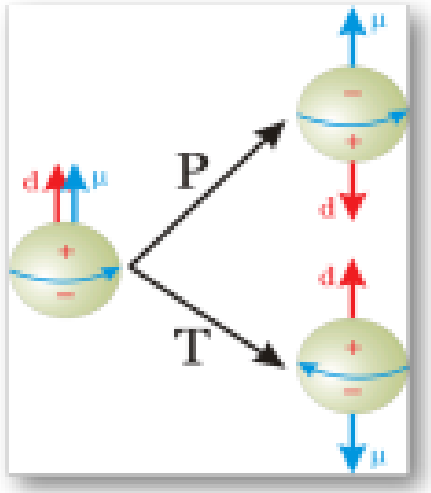
- **Energy of magnetic dipole** invariant under P and T:

$$-\vec{\mu} \cdot \vec{B} \overset{P \text{ or } T}{\longrightarrow} -\vec{\mu} \cdot \vec{B}$$

  No other direction than spin $\Rightarrow$ $\vec{d}$ parallel to $\vec{\mu}$ ($\vec{s}$).

- **Energy of electric dipole** $H = -\vec{d} \cdot \vec{E}$, includes term

$$\vec{s} \cdot \vec{E} \overset{P \text{ or } T}{\longrightarrow} -\vec{s} \cdot \vec{E}, \qquad (1)$$



EDMs violate both P and T symmetry

- EDMs possibly constitute the missing cornerstone to explain surplus of matter over antimatter in the Universe.
  - Non-vanishing EDMs would add 4th quantum number to fundamental particles (besides m, q, and s).

Naive estimate of scale of nucleon EDM

(Okun, 1965)

From Khriplovich & Lamoreux [4] and Nikolaev [5]:

- CP and P conserving magnetic moment $\approx$ nuclear magneton μ_N.

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\,\mathrm{e\,cm}.$$

- A non-zero EDM requires:
  - P violation: price to pay is $\approx 10^{-7}$, and
  - CP violation (from K decays): price to pay is $\sim 10^{-3}$.
- In summary:

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\,\mathrm{e\,cm}}$$

- In Standard model (without θ_{QCD} term):

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-24}\,\mathrm{e\,cm} \sim 10^{-31}\,\mathrm{e\,cm}}$$

Region to search for Beyond Standard Model (BSM) physics

- from nucleon EDMs with $\theta_{\mathrm{QCD}} = 0$:

$$\boxed{10^{-24}\,\mathrm{e\,cm} > |d_N| > 10^{-31}\,\mathrm{e\,cm}}.$$

PSI(2020): ultracold neutrons

$d_n < 1.8 \times 10^{-26}$ e cm --- about ultimate limit with neutrons, possible improvements by at most factor 10

Don't ask too much from dimensional estimates:

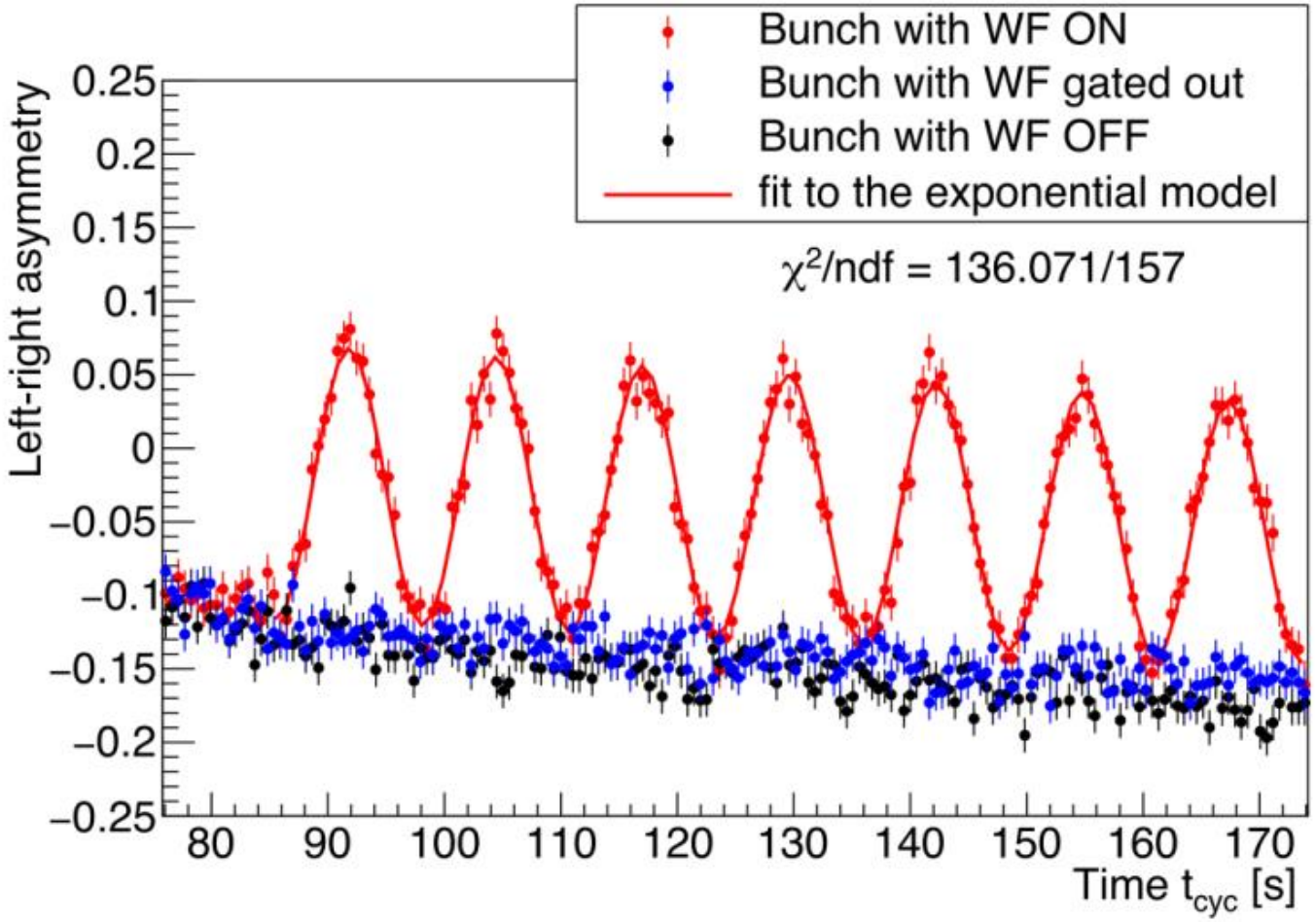
SM: Shabalin, 1978
Extra suppression by QCD coupling at electroweak scale

$d_n \sim 10^{-34}$ e cm

Confirmed by later studies

Comagnetometry for continuous spin flips to maintain the spin resonance: monitor the in-plane precession of gated out pilot bunch

JEDI, J. Slim et al. *Phys.Rev.Res.* 7 (2025) 2, 023257



Fast switches with switch time of < 10 ns

Frozen-spin

Spin-precession of particle MDM *relative* to direction of flight:

$$\vec{\Omega} = \vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{cyc}} = -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]. \quad (3)$$

$\Rightarrow \vec{\Omega} = 0$ **called frozen spin, because momentum and spin stay aligned.**

- In the absence of magnetic fields ($B_{\perp} = \vec{B}_{\parallel} = 0$),

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \quad (4)$$

  - Possible for particles with $G > 0$: proton ($G = 1.793$) or electron ($G = 0.001$).

For protons: (4) $\Rightarrow$ *magic momentum*:

$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\ \mathrm{MeV\,c^{-1}}} \quad (5)$$

Yu. Orlov et al. (BNL → srEDM)

Dedicated all electric proton EDM ring

Holy Grail of 10^{-29} e cm : based on no systematics but purel statistics and spin coherence time considerations

15 orders < MDM

Appetizer list on srEDM

- Conventional RF flipper (solenoid, waveguide Wien filter) NMR spin flips f~ 0.1-1 Hz
- Feasible pEDM rotation in all electric frozen-spin ring ~ 0.1 nHz ideally could yield sensitivity pEDM ~ 10^{-29} e cm for 1 year run
- Required record idle deuteron spin coherence time ~ 1000 s has been achieved by JEDI Collab.
- Elimination of the background from magnetic moment rotation is a must
- Factor 30 background from the Earth gravity pull (Y.Obukhov, A. Silenko, O. Teryaev (2007,20016); Y.Orlov, E.Flanagan, Y. Semertsidis (2012), N. Nikolaev et al. (2019))
- GR geometric magnetic field from the Earth rotation (S. Vergeles, N. Nikolaev)
- Betatron oscillation analysis prefers hybrid all electric ring with magnetic focusing quadrupoles: srEDM takes an ambitious stand that simulations are sufficient
- Yu. Senichev et al.: frequency domain method --- measuring spin-flip frequency may prove much more proficient than measuruing the spin rotation angle (recall the neutron EDM expts with hybrid E+B fields)
- JEDY@COSY: it is hard to eliminate longitudinal imperfection magnetic fields at the 10^{-4} level in all magnetic storage rings --- they do not affect the beam trajectory and can not be assessed by the beam dynamics.

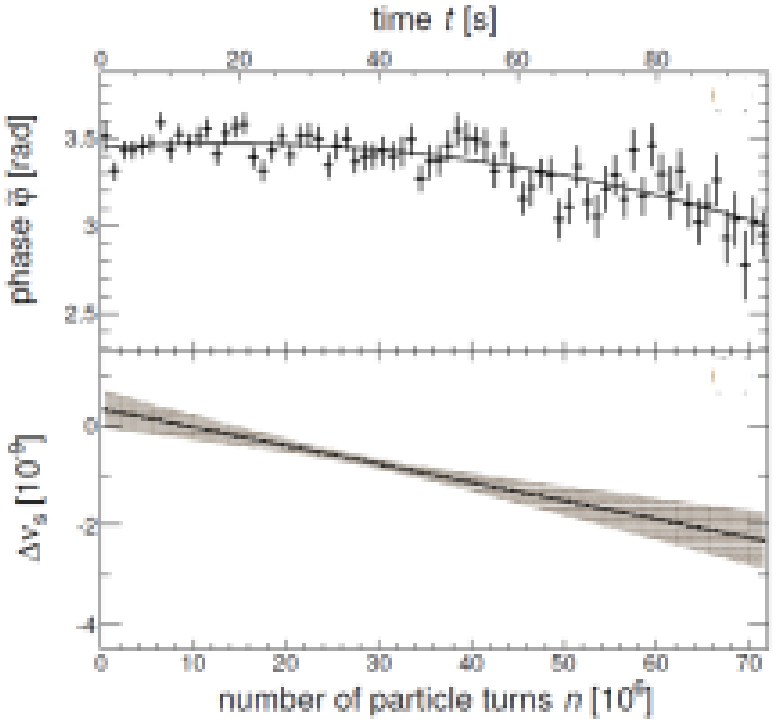
Precision determination of the spin tune [13] II

JEDI Collab. @ COSY

Precise time-stamping of events,

- allows us to monitor phase of measured asymmetry with (assumed) fixed spin tune ν_s in a 100 s cycle:

$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \qquad (9)$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$



Origin of frequency walk:
hystereis in magnets?
unstable temperature?

COSY was not designed as even 10^{-6} ring

Experimental technique allows for:

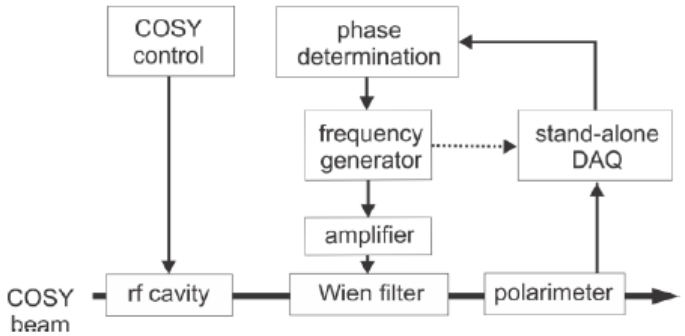
- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.
- $\Rightarrow$ **new precision tool to study systematic effects in a storage ring.**

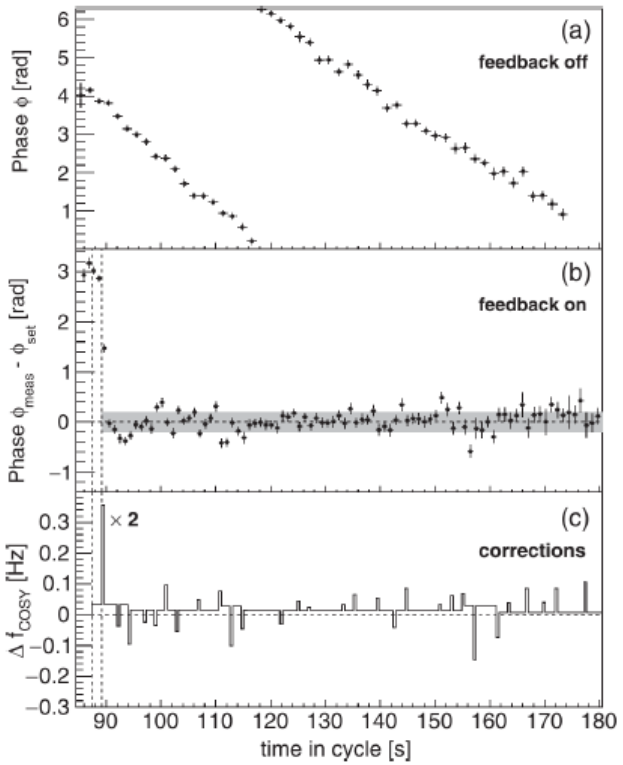
Excellent example of Ramsay's theorem in action

Phase locking spin precession in machine to device RF

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)





Major achievement : Error of phase-lock $\sigma_\phi = 0.21$ rad [18].

A uniqe case of self-comagnetometry in idle precession vs. standard two-species comagnetometry

CP Puzzle in QCD: P & T violating

$$L_{\bar\theta} = -\frac{1}{32\pi^2}\bar\theta g_S^2 G^{a\mu\nu}\tilde G^a_{\mu\nu} \qquad \tilde G^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{a\rho\sigma}$$

preserves renormalizibilty

$$G^{a\mu\nu}\tilde G^a_{\mu\nu} = \partial_\mu K^\mu\,, \qquad K^\mu = \epsilon^{\mu\nu\rho\sigma}\left(A^a_\nu G_{\rho\sigma} - \frac{1}{3}g_s f^{abc}A^a_\nu A^b_\rho A^c_\sigma\right)$$

Unobservable in perturbation theory, but Adler-Bell-Jackiw anomaly and instanton vacuum give observable CP violation

$$L_{CPV} = 3m^*\bar\theta(\bar\Psi i\gamma_5\Psi)\,. \qquad m^* = \frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s} \approx \frac{m_u m_d}{m_u + m_d}$$

Exact Peccei-Quinn chiral symmetry $U(1)_{PQ}$ if there is a massless quark

EDM of nucleons $\quad d_N \sim \bar\theta\frac{m^*}{\Lambda_{QCD}}\mu_N \approx \bar\theta\times 10^{-16}\ \mathrm{e\cdot cm}$

PSI (2020): $\quad d_n < 1.8\times10^{-26}\mathrm{e\cdot cm.}$ → $\quad \bar\theta \sim 10^{-10}.$

Swap the QCD angle for the dynamic pseudoscalaar field: $\quad \bar\theta \to \frac{1}{f_{(a)}}a(x)$

Spontaneous breaking of $U(1)_{PQ}$ → light pseudoscalar axion as a likely source of dark matter

Weinberg (1978) from πNN to aNN → $-\frac{\hbar}{2f_{(a)}}g_f\partial_\mu a(x)\overline{\Psi}\gamma^\mu\gamma_5\Psi \qquad m_{(a)} \approx m_\pi\frac{f_\pi}{f_{(a)}}\frac{\sqrt{m_u m_d}}{m_u+m_d}\,,$

Relic axion dark matter

Coherent axion galactic halo $a(x) = a_0 \cos\left(\omega_{(a)} t - \boldsymbol{k}_{(a)} \cdot \boldsymbol{x}\right)$

$$\omega_{(a)} = \frac{m_{(a)} c^2}{\hbar} \qquad a_0 = \frac{1}{m_{(a)}} \sqrt{\frac{2\rho_{\rm DM}\hbar}{c^3}}$$

Preskill, Wise, Wilczek (1983)
Abbott, Sikivie (1983)
Dine, Fischler (1983)
Review: Sikivie (2021)

Oscillating EDM $d_{\rm N}^{(a)}(x) = \frac{a(x)}{f_{(a)}} \kappa_{(a)} \frac{\mu_{\rm N}}{c}$

Axion halo acts on spin as a psedomagnetic field (P. Vorobiev, I.Kolokolov, I. Fogel (1989), R. Barbieri (1989))

Spins in storage rings move ~1000 times faster than Earth w.r.t. galatic halo axions → enhanced pseudomagnetic field, Foldy-Wouthuysen treatment is mandatrory Silenko (2022)

Instantaneous spin rotation $\boldsymbol{\Omega}^{(a)} = \frac{a_0}{f_{(a)}} \left[g_{\rm f} \omega_{(a)} \sin\left(\omega_{(a)} t\right) \frac{\boldsymbol{v}}{c} - \kappa_{(a)} \gamma \cos\left(\omega_{(a)} t\right) \frac{\boldsymbol{v}}{c} \times \boldsymbol{\Omega}_{\rm c} \right]$

pseudomagnetic field (= rf solenoid) oscillating EDM (= Wien filter)

$\pi/2$ phase shift of two spin rotators with orthogonal spin rotation axes --- spin rotations are in sync

Axion induced resonance spin-flip angular velocity Silenko (2022), NNN (2022)

$$\Omega_{\rm res} = \frac{a_0}{2 f_{(a)}} \frac{v}{c} \gamma \left| g_{\rm f} G - \kappa_{(a)} \right| \Omega_{\rm c}$$ is independent of the spin-axion phase difference

Axion mass is unknown: need a broadband antenna and keep tuning till we hit the right frequency

Dynamics of the Froissart-Stora scan: axion phase ambiguity

Duration of the spin-jump must be shorter than the axion coherence time $\tau_a = \frac{h}{m_a v^2}$,

JEDI sensitive to m_a = 0.5 neV, lab velocity wrt axions halo v ~10^{-3} →

$\tau \sim 10$ s, tune ramp rate properly

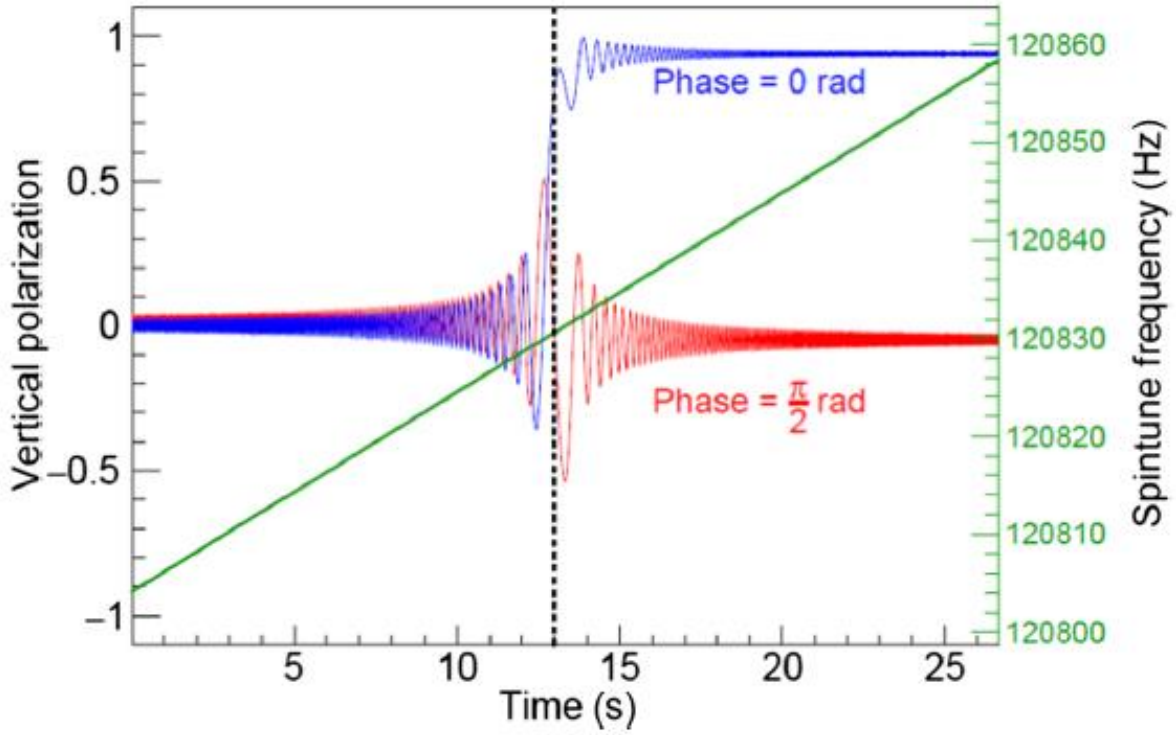
At least 1 s for single determination of the spin phase

Spin-flip frequency is independent of the entirely unknown relative spin-axion phase Δ

But the resonant spin jump is ~ cos Δ

Multiple bunch solution for the phase problem

N.B. Rotation of spin from the initial vertical to the horizontal one is entirely free of the phase ambiguity → axion signal is an emergence of the precessing in-plane polarization → JEDI Fourier technique



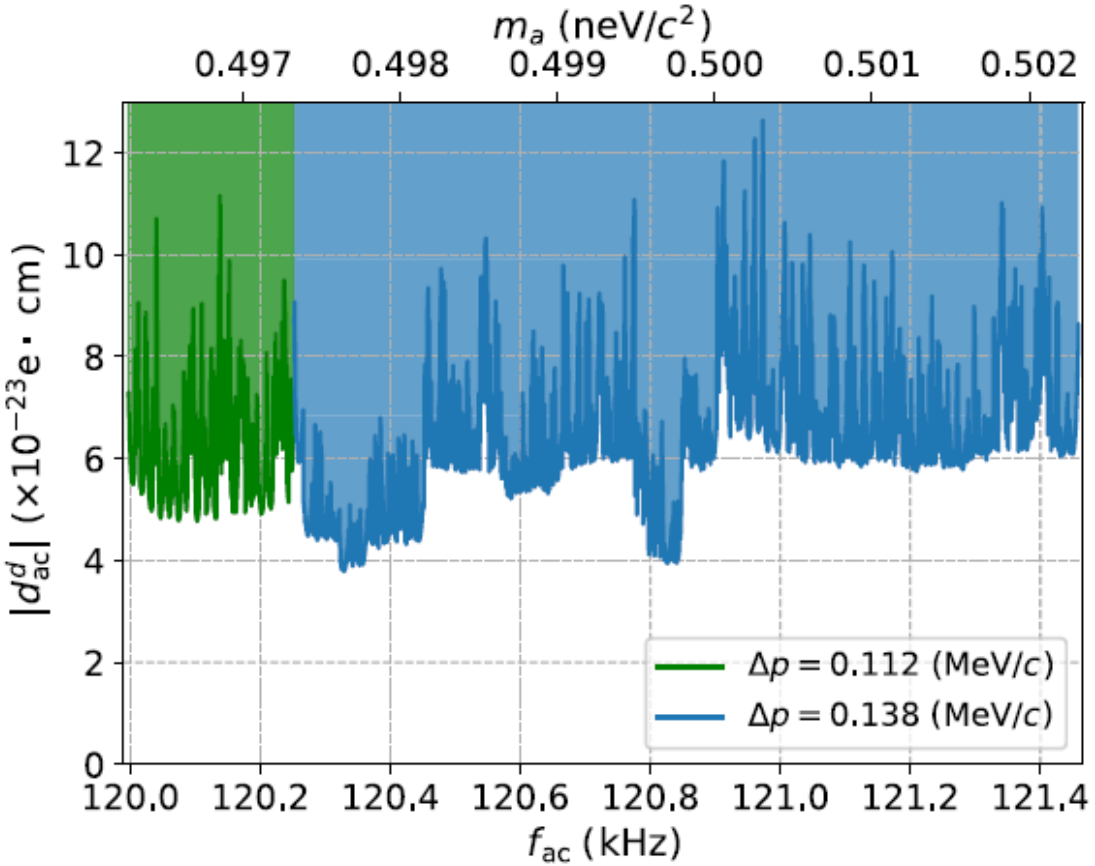
JEDI @ COSY

Tune antenna rampimg beam energy

Altogether 103 ramps

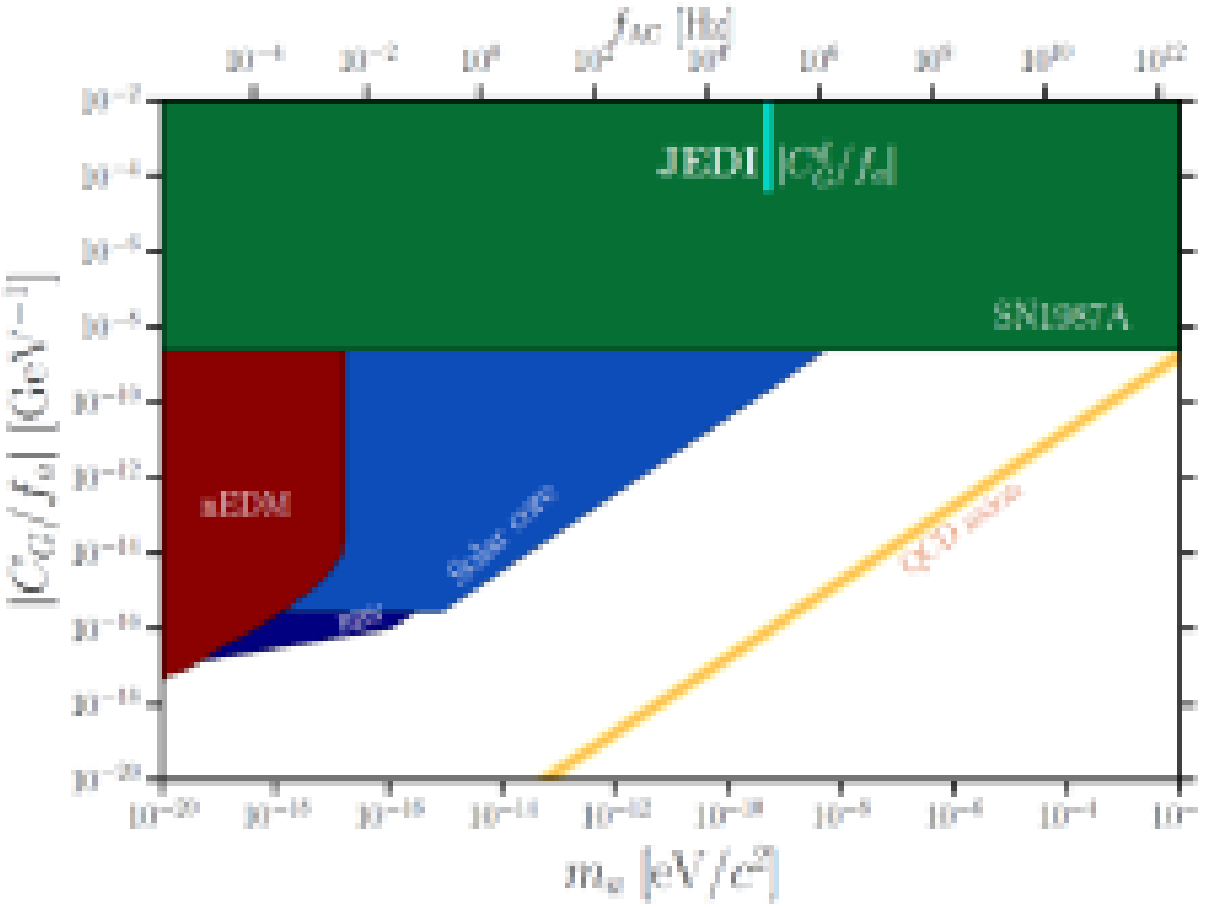
Frequency range 120-121.4 kHz

Axion mass range 4.95-5.02 neV/c^2

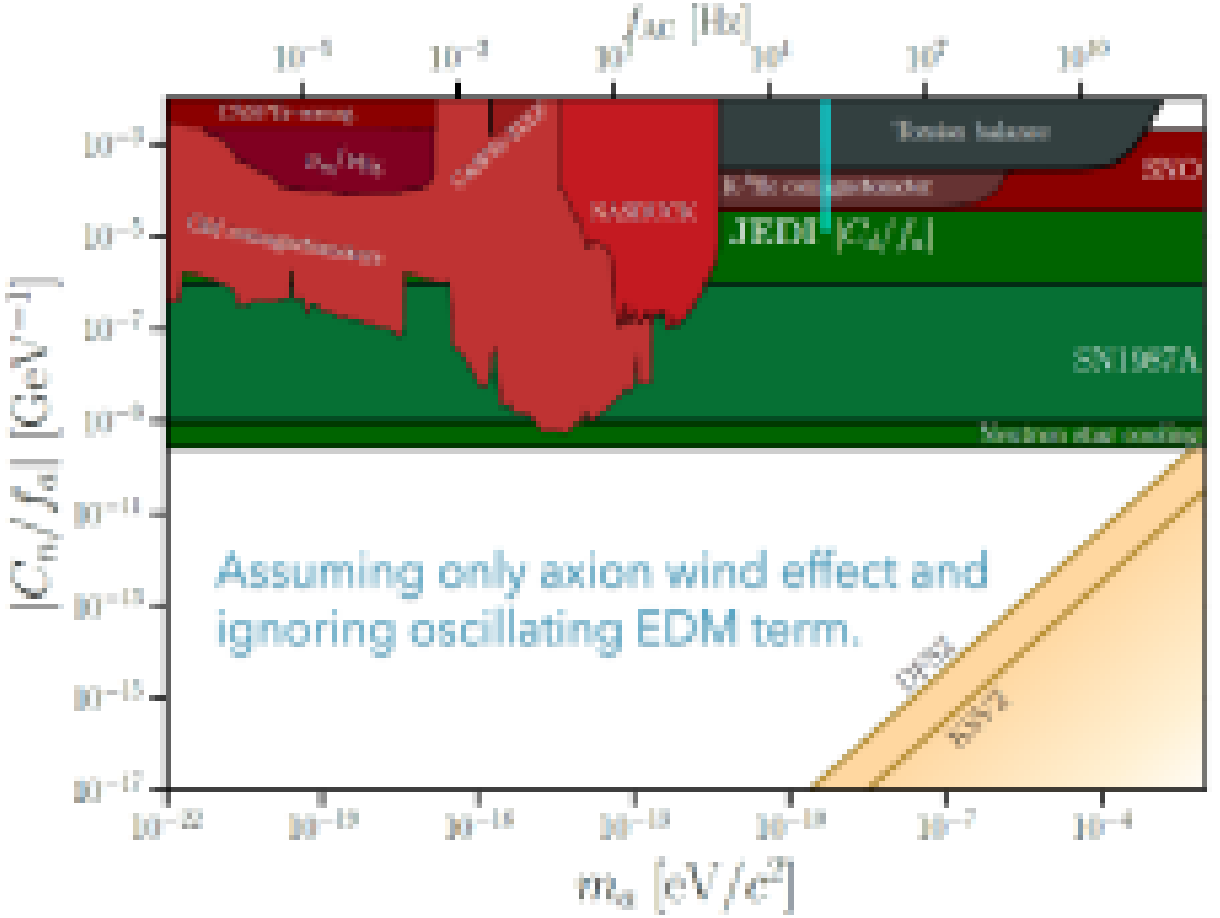


90% confidence level sensitivity for excluding the axion (ALP) induced oscillating EDM of the deuteron (assuming the EDM dominance)

Basically no direct experimental upper bounds in the PDG tables on the static EDM of bare protons and deuterons to compare with



ALP-gluon coupling, assuming 100% oscillating EDM.



ALP-nucleon coupling, only axion wind effect, ignoring oscillating EDM term.

Modest bound? Stay open minded about ALP's

Axions at PTR and NICA facility(Nuclotron) NNN (2022)

PTR (CPEDM): prototype hybrid E+B confinement of 45 MeV frozen spin protons on orbit (non-ideal for polarimetry)

Prime motivation: sqrutiny of the frozen spin approach to a search for the EDM of protons

Cyclotron frequency $$\boldsymbol{\Omega}_c = \frac{q}{m\gamma}\left(-\boldsymbol{B} + \frac{\boldsymbol{v}\times\boldsymbol{E}}{v^2}\right)$$

Frozen spin $$\boldsymbol{\Omega}_s^{\mathrm{mdm}} = \frac{q}{m}\left\{-G\,\boldsymbol{B} + \left(G - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{v}\times\boldsymbol{E}}{c^2}\right\} = 0$$ → zero mass axion antenna

$$\boldsymbol{\Omega}_s^{\mathrm{edm}} = -d\{\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}$$

Lift the frozen spin condition $$\Delta\boldsymbol{B} = \frac{1}{v^2}[\boldsymbol{v}\times\Delta\boldsymbol{E}]$$

The axion resonance at $$\omega_a = -G_p\gamma\Omega_c\frac{\Delta E}{E_0}$$, broadband axion antenna: ~ 0-0.5 MHz

Change of paradigm for protons: look for axion inducrd buildup of precessing in-plane polarizatioin

- NICA with bypasses
- Modified Nuclotron with extended straight sections (Yu.N. Senichev's et al.)

- **Why not a dedicated ring in China?**

NICA as a hybrid axion antenna with E+B bypasses

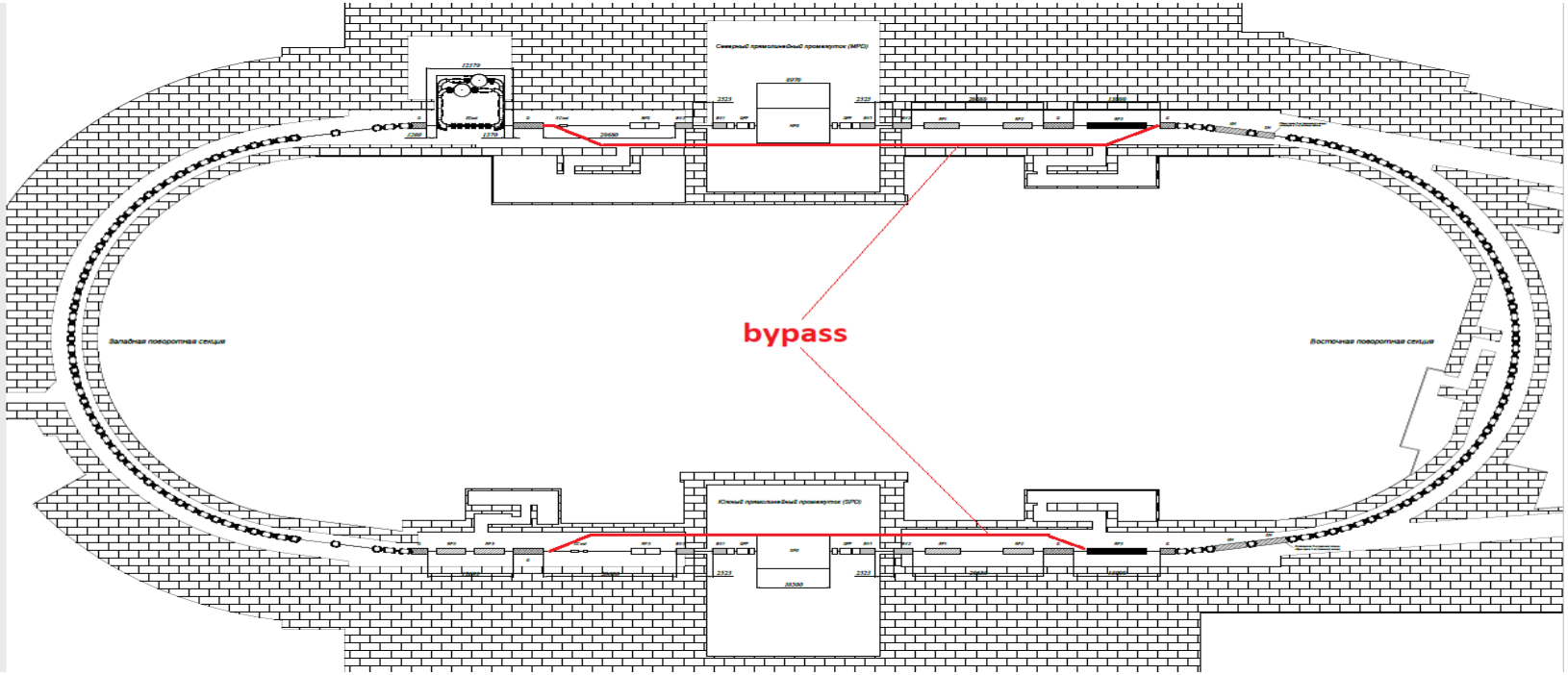
Y. Senichev et al. (2022)
More in Senichev's talk

Prime motivation: quaisi-frozen deuteron spin at NICA to search for the deuteron EDM

Two approx. 100 m bypasses will endow NICA with partial features of PTR

Bypasses with magentic dipoles and electric deflectors act on spin as **static** WFs

Bypass guarantees no interference with SPD and MPD operation !



Still better: long straight sections in the new Nuclotron (under discussion)

Bypass/Straight sections

- Scan maintaining the integral Wien filter features
- Effective length of the Wien filter per straight section ~ 10 m
- Band width at a fixed energy and orbit

$$\Delta f_s = \frac{(1+G)\, q\, E\, L}{2\pi\, mc^2\gamma^2\beta^2} f_{rev} \rightarrow 2 \times 15/\gamma^2\beta \text{ kHz}$$

- Polarimetry preferred proton energy ~270 MeV
- Protons: axion resonance buildup of the horizontal polarization
- Need time-stamped polarimetry for detection of the precessing horizontal polarization
- Fourier analysis of oscillating horizontal polarization is basically free of systematics
- Advantage of protons: larger magnetic anomaly, higher idle precession frequency

What is the state of art in PV?

SIN (PSI): pp elastic scattering at 45 MeV (SIN), several years of running, S. Kystrin et al. PRL 58 (1987) 1616

$A_{PV} = (1.5 +/- 0.22)\ 10^{-7}$

Consistent with expectations from low-energy meson exchange model

ANL ZGS: p(H_20), 5.1 GeV, Nigel Lockyer et al. Phys.Rev. D30 (1084) 860

$A_{PV} = (26.5 +/- 6.0 +/- 3.6\ )\ 10^{-7}$

None of theorists has ever been able to explain this gigantic effect

High sensitivity PV expt with oscillating beam helicity

Landau-Budker team: I. Koop, A. Mil'shtein, N. Nikolaev, A.Popov, S.Sal'nikov, P. Shatunov, Yu. Shatunov, Physics of Particles and Nuclei, 52(4), 549-554 (2021)

Store vertically polarized beam

Fast (< 1 s) rotation of spin from vertical to the in-plane by RF spin flipper

JEDI: the precessing spin phase is measured by JEDI time-stamp of oscillating within 1-2 s

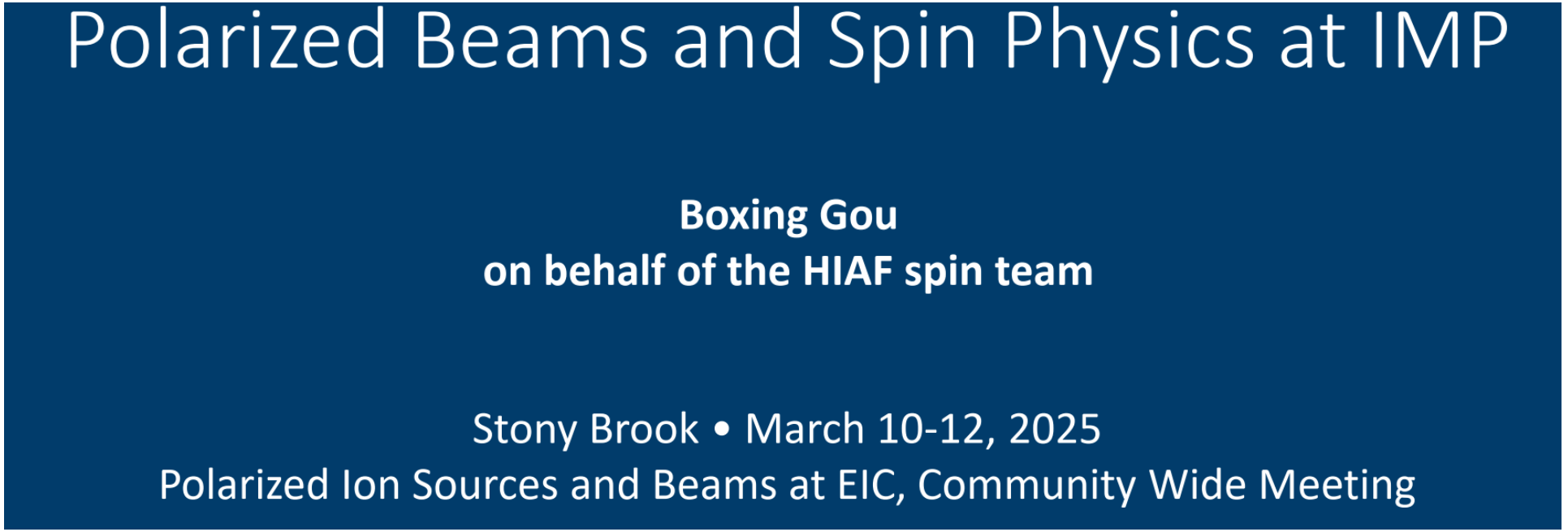
Single-turn extraction of the bunch of known helicity:

Measure current upstream and downstream of a bulk target

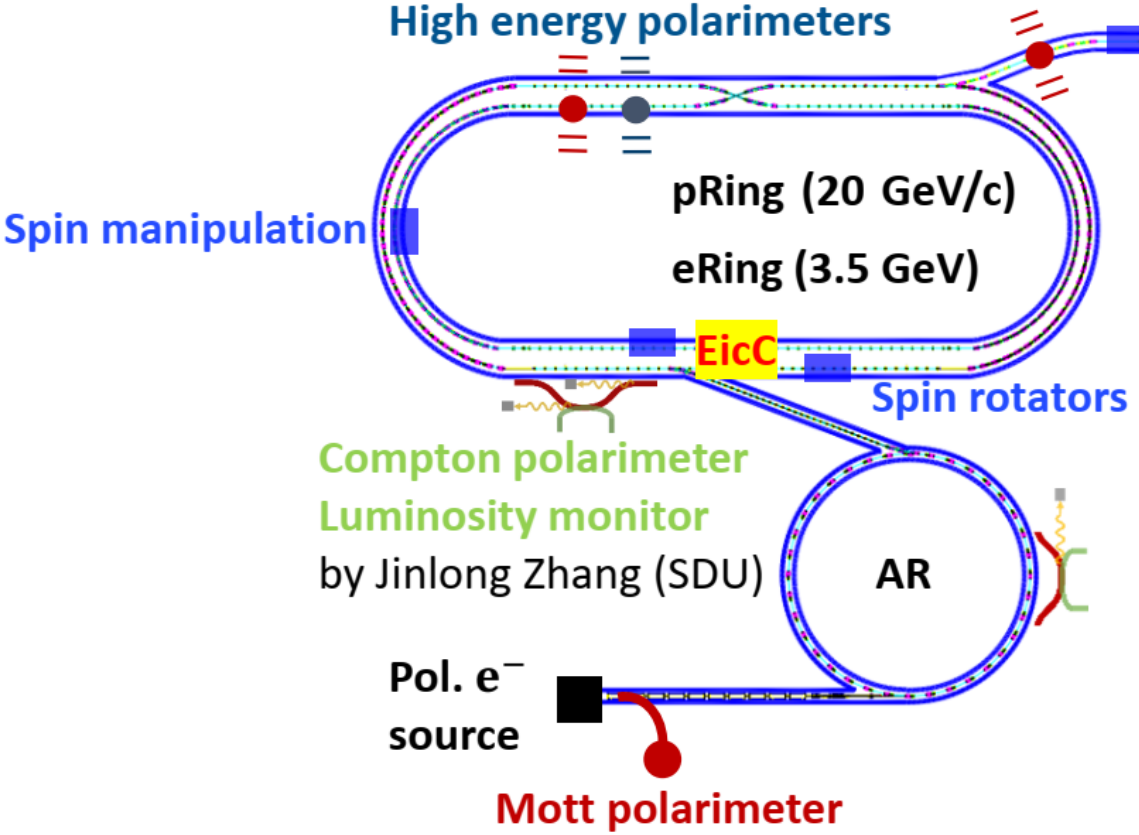
Fourier analyze the observed attenuation

5 s cycle are feasible → > 5×10^5 cycles per month → 10^{-8} PV asymmetry is within reach

- Millistrong TVPC interaction: bridge to China



HIAF-EicC



High Intensity Heavy-ion Accelerator Facility (HIAF)

✓ **to be commissioned in 2025**

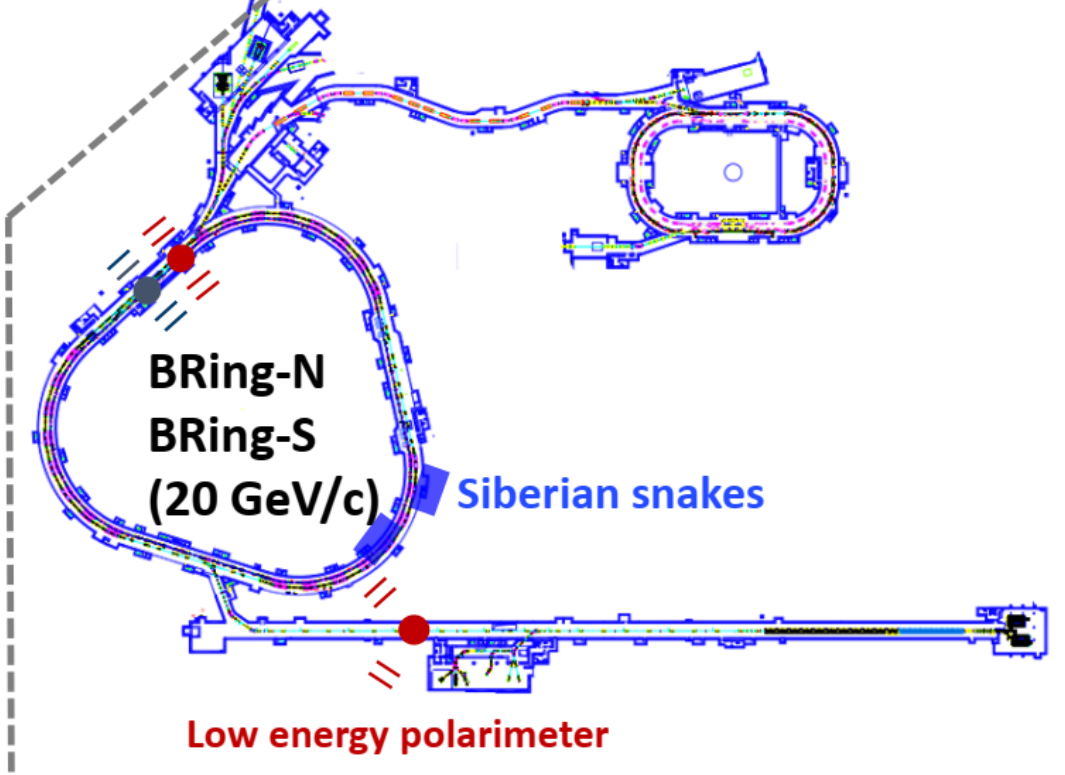
Zhou et al. AAPPS Bulletin (2022) 32:35
https://doi.org/10.1007/s43673-022-00064-1

AAPPS Bulletin

REVIEW ARTICLE Open Access

Status of the high-intensity heavy-ion accelerator facility in China

Xiaohong Zhou*, Jiancheng Yang and the HIAF project team



Electron ion collider in China (EicC)

- currently being proposed
- initial driving force of polarized beam development at IMP

TVPC observable in pd total X-section

$$\sigma_{\rm tot} = \sigma_0 + \sigma_{\rm TT}\left[\left(\mathbf{P}^{\rm d}\cdot\mathbf{P}^{\rm p}\right) - \left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right)\right]$$
$$+ \sigma_{\rm LL}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma_{\rm T} T_{mn}k_m k_n$$
$$+ \sigma^{\rm p}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma^{\rm d}_{\rm PV}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)$$
$$+ \sigma^{\rm T}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) T_{mn}k_m k_n$$
$$+ \sigma_{\rm TVPV}\left(\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]\right)$$
$$+ \sigma_{\rm TVPC} k_m T_{mn}\epsilon_{nlr} P^{\rm p}_l k_r\,.$$

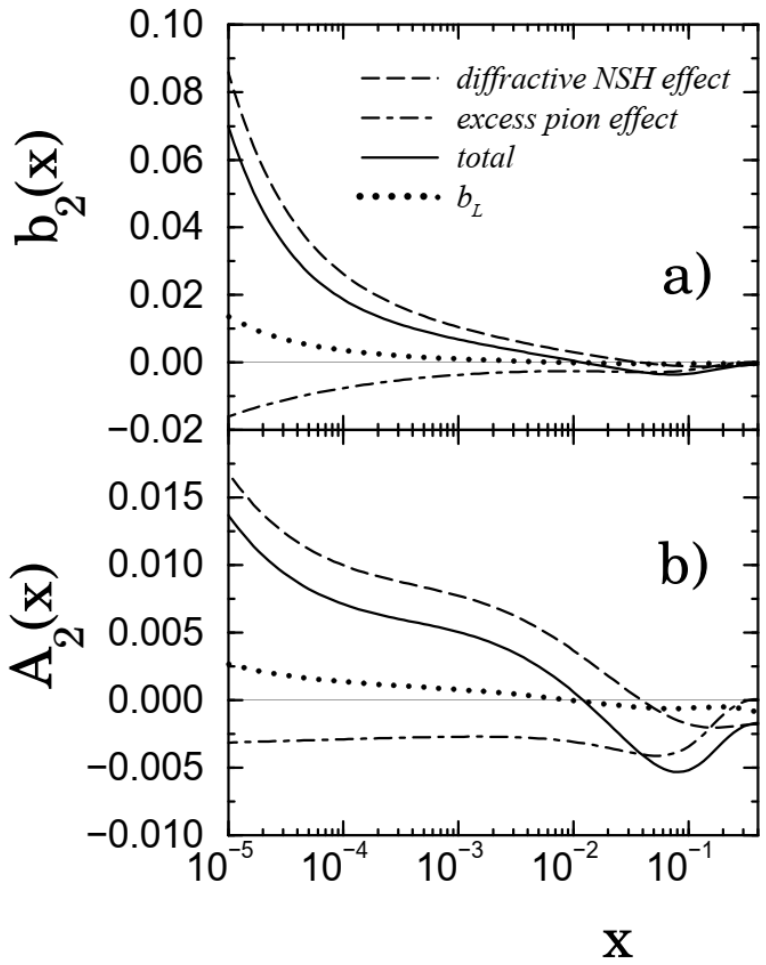
Y-axis is normal to the ring plane

Z-axis **k** is a collision axis along the beam momentum,

$$k_m T_{mn}\epsilon_{nlr} P^{\rm p}_l k_r = T_{xz}P^{\rm p}_y - T_{yz}P^{\rm p}_x\,.$$

Off-diagonal tensor polarization is a must for the T-violation signal

DIS on tensor polarized deuterons



Tensor structure functions are unique for spin-1 targets

Conservative np approximation for the deuteron: nonperturbative nuclear pion excess and eclipse effects have interesting x_{bj}-dependence in the kinematical domain if IMP EIC @ HIAF

N.N. Nikolaev, W. Schäfer, *Nonvanishing tensor polarization of sea quarks in polarized deuterons*, Phys. Lett. B 398 (3-4), 245-251 (1997)

Large x > 1: tensor-polarization dependent Fermi-motion

Admixture of 6q-states ?

T- and C-violation don't come for free

Non-renormalizable meson-exchange effective interaction (Simonius, 1975)

$$\mathcal{L}^{TVPC}_{\rho NN} = i\sqrt{2}\bar{g}_\rho f_\rho \frac{\kappa_V}{2m_n}\bar{N}\sigma^{\mu\lambda}(\tau^-\partial_\lambda\rho^+_\mu - \tau^+\partial_\lambda\rho^-_\mu)N$$

Uzikov, Haidenbauer (2015,2016): strong numerical suppression → go after 10^{-6} signal!

Non-renormalizable T-odd EFT's : Kurylov et al. PRD 63 (2001) 076007

$$\begin{aligned}
\mathcal{O}^{ff'}_{7a} &= i\bar{\psi}_f\gamma_5\sigma_{\mu\nu}(\overleftarrow{D}_\nu + \overrightarrow{D}_\nu)\psi_f\bar{\psi}_{f'}\gamma^\mu\gamma_5\psi_{f'} + \text{ h.c.} \\
\mathcal{O}^{g\gamma}_{7b} &= \bar{\psi}_f\sigma_{\mu\nu}\lambda_a\psi_f G^{\mu\alpha}_a F^\nu_\alpha \\
\mathcal{O}^{Z\gamma}_{7c} &= \bar{\psi}_f\sigma_{\mu\nu}\psi_f Z^{\mu\alpha}F^\nu_\alpha \quad .
\end{aligned}$$

Found no tight connection between EDM and T-violation in scattering experiments

Intriguing unexplored possibility of a strong enhancement of C-violation at baryon number generation? How to handle non-renormalizable EFT's in early Universe? Mimic Simonus with multi-Tev ρ–mesons? Heavy photons? Good task for students.

Systematics-free NMR TVPC signal in storage ring pd expt with rf spin flipper (solenoid)

$$\vec{S}(n) = S_y(0)[\cos(\epsilon n)\vec{e}_y + \sin(\epsilon n)[\cos(\theta_s n)\vec{e}_x - \sin(\theta_s n)\vec{e}_z]$$

$$T_{yy}(n) = \frac{1}{2}T_{yy}(0)\cdot\left[-1+3\cos^2\epsilon n\right],$$

$$T_{xx}(n) = \frac{1}{2}T_{yy}(0)\cdot\left[-1+3\sin^2\epsilon n\cdot\cos^2\theta_s n\right],$$

$$T_{zz}(n) = \frac{1}{2}T_{yy}(0)\cdot\left[-1+3\sin^2\epsilon n\cdot\sin^2\theta_s n\right],$$

$$T_{yx}(n) = \frac{3}{2}T_{yy}(0)\cdot\sin\epsilon n\cdot\cos\epsilon n\cdot\cos\theta_s n,$$

$$T_{yz}(n) = -\frac{3}{2}T_{yy}(0)\cdot\sin\epsilon n\cdot\cos\epsilon n\cdot\sin\theta_s n,$$

$$T_{xz}(n) = -\frac{3}{4}T_{yy}(0)\cdot\sin^2\epsilon n\cdot\sin 2\theta_s n.$$

Stored polarized deuterons in a ring, atomic cell target with nuclear (proton) polarized hydrogen atoms

Initial vertical beam polarization

$$T_{xx}(0) = T_{zz}(0) = -\tfrac{1}{2}T_{yy}(0).$$

$$T_{yx}(0) = T_{yz}(0) = T_{xz}(0) = 0$$

→ **Unique systematics free Fourier signature of T-violation.**

Enhance uniqueness by target spin flips

N.N. Nikolaev, F. Rathmann, A.J. Silenko, Yu. Uzikov, Physics Letters B 811, 135983 (2020);

Cherry on a cake: a change of the paradigm

Nikolaev-Rathmann-Slim-Uzikov (Landau-BNL-Aachen-Dubna)

Boxing Gou at al., IMP, Lanzhou

- Store and accelerate polarized protons
- Polarized deuterons in the atomic cell target
- Vertical holding field in the cell ←→ the guiding field in the storage ring
- RF solenoid locked to spin precession in the holding field
- Fourier analysis gives accces to all the polarization asymmetries with exception of the longitudinal beam polarization asymmetries
- Add flipper of proton spins in the ring to realize the Landau-Budker generation of oscillating longitudinal polarization
- Fantastic potential of measuring all the possible spin asymmetries in one go!
- Boxing Gou has in mind a closely related but somewhat different rotation of the target spin: maybe he could comment on that online?

Summary

- Great to welcome China in the spin physics club
- Don't overlook a chance to pursue open issues with fundamental symmetries
- Only versatile new facilities !
- Dedicated BSM axion & EDM & T-violation rings?
- Major challenges: high sensitivity and scrupulous study of systematics
- Profit from Fourier identification of oscillating spin asymmetries
- Great potential of internal targets with oscillating deuteron polarization

Thank your for patience and attention

- Selected references

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- Pseudomagnetic field and NMR phenomena: P.V. Vorov'ev, I.V. Kolokolov, V.F. Fogel, JETP Lett., 50, 65 (1989)
- Reviews: P. Sikivie, Rev. Mod. Phys., 93 (1), 015004 (2021) and references therein
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- D.Salnikov et al., JETP Lett.,**117**, 889–897 (2023)
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- Oscillating EDMs: P.W. Graham et al., Phys. Rev. D97, 055006 (2018)
- Axions in storage rings: J. Pretz et al., Eur. Phys. J., C80, 107 (2020)
- A. Silenko, Eur. Phys. J., C82, 856 (2022)
- N. Nikolaev, JETP Lett. 115(11), 523 (2022)
- JEDI@COSY: first search for axions in SR : S. Karanth et al. , Phys. Rev. X., 13? 031004 (2023) and extensive list of references therein
- Axions and EDM at NICA: Y. Senichev et al., J. Phys: Conf. Ser. 2420, 012052 (2023); JACoW Publ., IPAC-22, 492 (2022)

1. Senichev Y, Aksentev A, Ivanov A and Valetov E., Frequency domain method of the search for the deuteron electric dipole moment in a storage ring with imperfections, preprint arxiv:1711.06512 [physics.acc-ph], 2017

2. A E Aksentev and Y V Senichev, Frequency domain method of the search for the electric dipole moment in a storage ring, J. Phys. Conf. Ser.1435, 012026 (2020), URL https://doi.org/10.1088/1742-6596/1435/1/012047.

3. A. A. Melnikov, Yu. V. Senichev, A. E. Aksentyev, S. D.Kolokolchikov, The nature of spin decoherence of a polarized beam of light nuclei in a storage ring for EDM search, JETP Letters, 118 (2023) 713-720

Supplement slides

Bunch-selective spin manipulation → co-magnetometry II

World-first (September 2020 JEDI, with d at 970 MeV/c)

See recent JEDI preprints for more details:

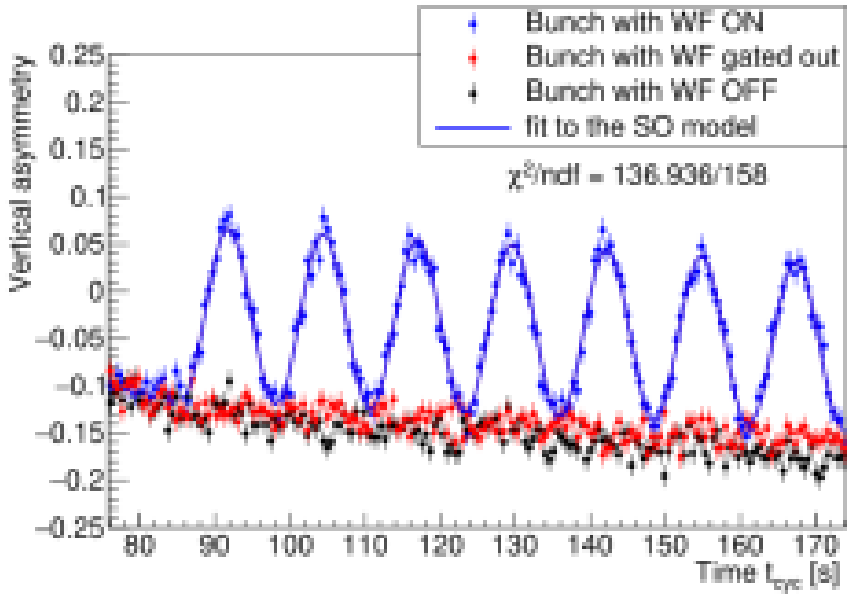
- *Pilot bunch and co-magnetometry of polarized particles stored in a ring* [15]
- *Spin decoherence and off-resonance behavior of radiofrequency-driven spin rotations in storage rings* [16]

J. Slim et al., 2309.06561 [physics.ins-det]

N. Nikolaev et al., 2309.05080 [physics.acc-ph]

Synchrotron-oscillations model [16]:

$$A_{sy}(t) = a(t - t_0) + b + \frac{c}{\sqrt{1 + [2\pi Q_{sy} f_{SF}(t - t_0)]^2}} \times \cos\left[2\pi f_{SF}(t - t_0) - \arctan(2\pi Q_{sy} f_{SF}(t - t_0))\right]$$



Works close to perfection

- allows spin manipulations on *individual* stored bunches **on flattop**
- application of principle on the horizon for EIC and NICA

Testing SM by Parity Violation (PV)

- The observable: PV beam helicity dependence of the total X-section and elastic scattering
- New approach: single turn extraction of horizontal polarized beam onto extrenal target--- time-tag control of the extracted horizontal beam helicity
- A challenge to experimentalists: the expected asymmetries are few 10^{-8} to 10^{-7} --- counting events is entirely hopeless, measure beam current upstream and downstream thick nuclear target instead
- I.A. Koop, A.I. Milstein, N.N. Nikolaev, A.S. Popov, S.G. Salnikov, P.Yu. Shatunov, Yu.M. Shatunov, *Tests of Fundamental Discrete Symmetries at the NICA Facility: Addendum to the Spin Physics Programme*, Physics of Particles and Nuclei, 52(4), 549-554 (2021); Physics of Particles and Nuclei, 52(6), 1044-1119 (2021)
- Polarimetry requirements: < 1 GeV/c deuterons are favored
- High energy: B.G. Zakharov, Sov. J. Nucl. Phys. Sov. J. Nucl. Phys., 42 (3), 479-482 (1985)]

PV expt with deuterons extracted from Nuclotron – 2

Counting single events is unrealistic (?): measure the total charges of bunches in front of and behind the external target.

Non-invasive measurement of the beam charge by Rogowski coils

Bunched beam: signal from the Rogowski coil = the derivative of the beam current

Two integratons:

1-st integration → current of the bunch

2-nd integration → total charge in the bunch

Upstreasm and downstream families of 3-5 Rogowski coils for crosscheck and boosting the precision

The complementary polarimetry behind the target to monitor the polarization of the beam

PV asymmetries < 10^{-7} are within the reach in 1 month at NICA

High sensitivity PV expt with oscillating beam helicity

I.A. Koop, A.I. Mil'shtein, N.N. Nikolaev, A.S. Popov, C.G. Sal'nikov, P.Yu. Shatunov, Yu.M. Shatunov, Physics of Particles and Nuclei, 52(4), 549-554 (2021)

Store vertically polarized beam

Fast (< 1 s) rotation of spin from vertical to the in-plane by RF spin flipper

JEDI: the precessing spin phase is measured by JEDI time-stamp of oscillating within 1-2 s

Single-turn extraction of the bunch of known helicity:

Measure current upstream and downstream of a bulk target

Fourier analyze the observed attenuation

5 s cycle are feasible → > 5×10^5 cycles per month → 10^{-8} PV asymmetry is within reach

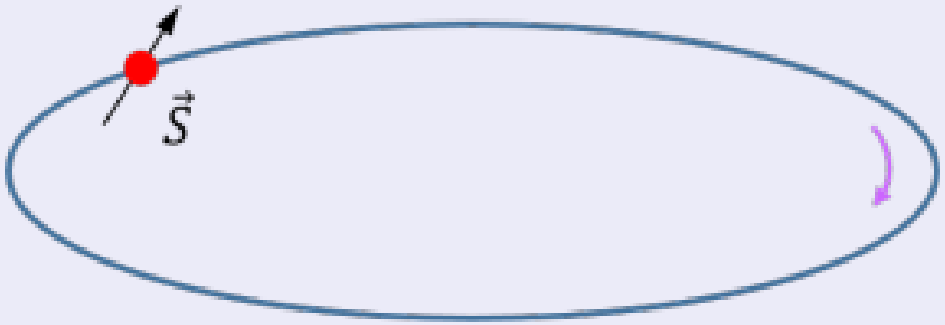
Spin precession of particles with MDM and EDM

In rest frame of particle

- Equation of motion for spin vector $\vec{S}$:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \quad (2)$$

With protons in a ring



→ Spin-precession with MDMs and EDMs described by Thomas-BMT Eq. [9].

N. Ramsey's theorem: frequency is a unique observable measureable to a very high precision

Ultracold neutrons: F.L. Shapiro (1967, JINR)

Breakthrough UCN experiment: I.S. Altarev et al. (1980, 1981, ЛИЯФ)

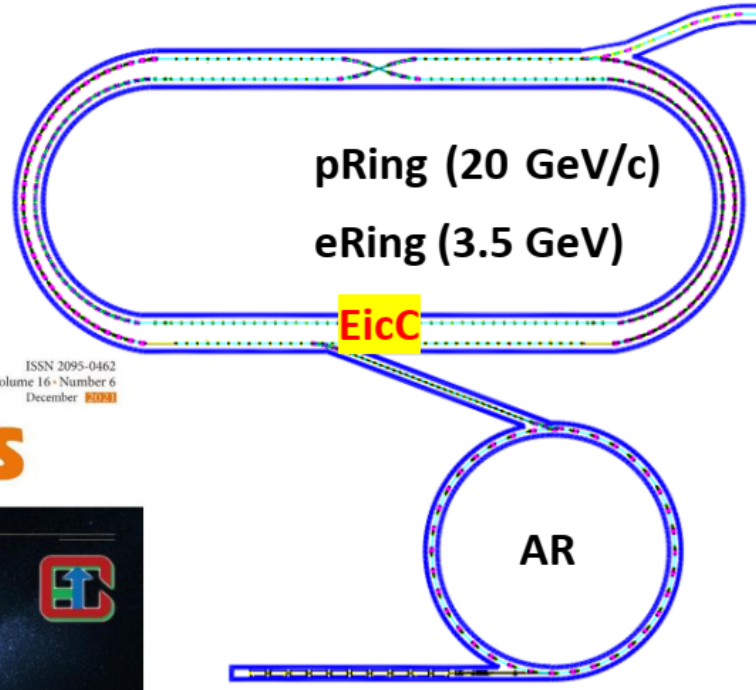
Neutron EDM: collinear E and B. Signal of EDM = shift of the spin precession frequency after flip of the electric field

Spin coherence time: crucial issue for protons

C. Weidemann et al., Phys. Rev. ST Accelerators and Beams, 18, 020101 (2015)

- 49.3 MeV protons in COSY
- Without spin-flips the vertical polarization lifetime (2.7 +/- 0.5) 10^3 s
- 99 spin flips during 300 s
- Flipping polarization lifetime 240 s.
- Strong evidence for the polarization loss by spin decoherence in the horizontal plane
- Arguablly the spin coherence time ~ $1/(G\beta^2\gamma)^2$ A.Lechrach et al. e-Print: 1201.5773 [hep-ex]
- Low energy protons are preferred
- More experimental scrutiny on stretchcing spin coherence time of protons is in order (sextupoles ?)

HIAF-EicC



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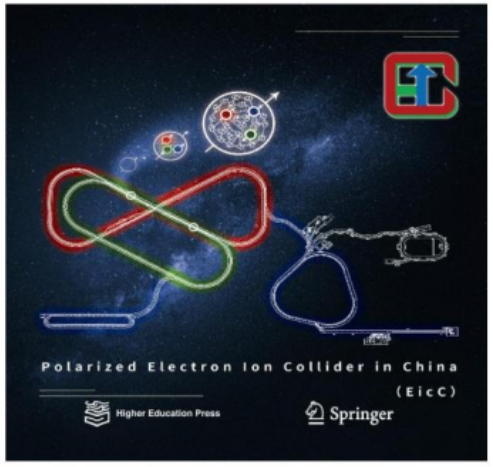


Electron ion collider in China (EicC)

- currently being proposed

High Intensity Heavy-ion Accelerator Facility (HIAF)

✓ to be commissioned in 2025

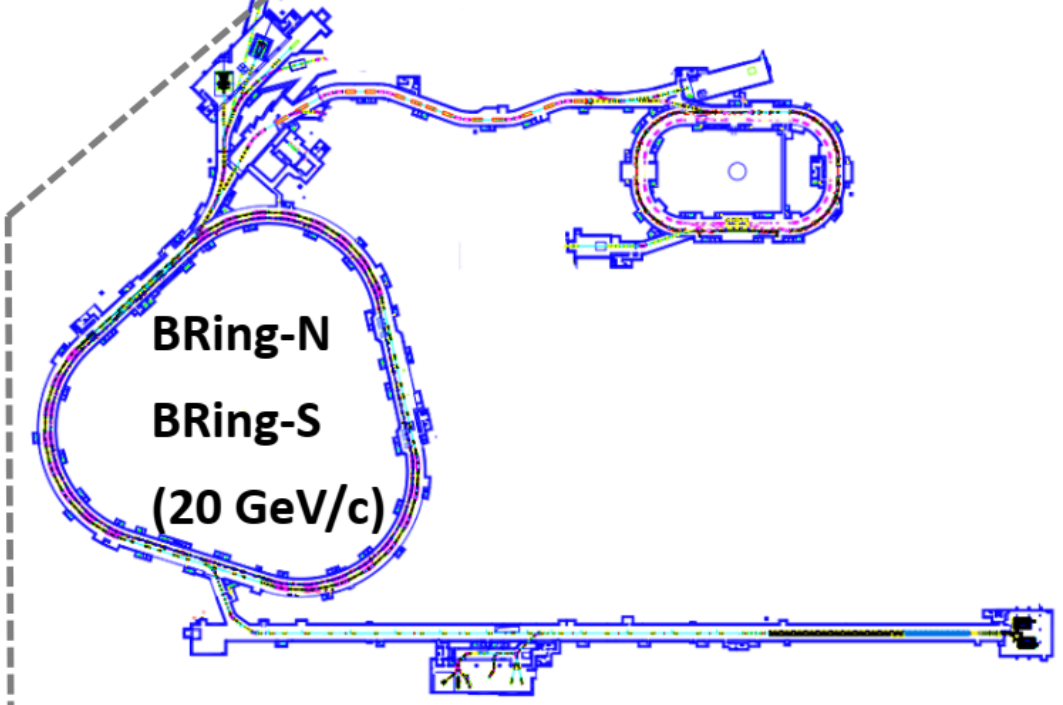
Zhou et al. AAPPS Bulletin (2022) 32:35
https://doi.org/10.1007/s43673-022-00064-1

AAPPS Bulletin

REVIEW ARTICLE Open Access

Status of the high-intensity heavy-ion accelerator facility in China

Xiaohong Zhou*, Jiancheng Yang and the HIAF project team



It is imperative to make storage rings a versatile spin physics workhorse

- Spin crisis important byt s not all
- Strong need for extension to fundamental symmetries; EDM, axions, parity and T-violation
  Review: S. Vergeles, N. Nikolaev, Y//et al., Usp.Fiz.Nauk 193 (2023) 2, 113-154;

  I.Koop et al *Phys.Part.Nucl.* 52 (2021) 4, 549-554

- New ideas on update of existing infrastructure of NICA complex
  Yu.N. Senichev et al., J.Phys.Conf.Ser. 2420 (2023) 1, 012052; JACoW IPAC2022 (2022), MOPOTK02

  Yu.N. Senichev, talk at this conference

Focus of this talk: spin of particles in storage rings as an axion antenna

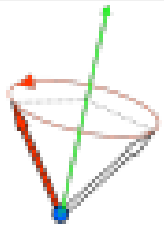
Basic approach: NMR-like signal in the pseudomagnetic field of axion halo in our galaxy

Spin coherence time

Most polarization experiments unaffected by coherence of spins along $\vec{n}_{co}$

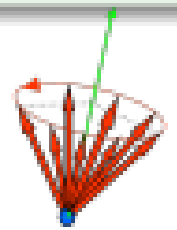
Spins aligned:

Ensemble *coherent*



Spin vectors out of phase:

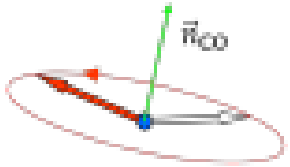
Ensemble *decoherent*



$\Rightarrow$ **Polarization along $\vec{n}_{co}$ not affected**

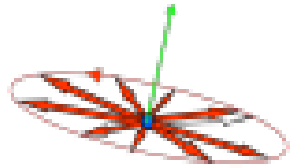
With frozen spins: $\vec{S} \perp \vec{n}_{co}$:

Spins aligned



With time:

Spins out of phase in horizontal plane



$\Rightarrow$ **In-plane polarization vanishes**

In machines with frozen spins:

Buildup time t to observe polarization $p_y(t)$ is limited by τ_{SCT}.

Proton spin lifetime in COSY: spinoff from spin filtering machine studies

C. Weidemann et al., Phys. Rev. ST Accelerators and Beams, 18, 020101 (2015)

- 49.3 MeV protons in COSY
- Without spin-flips the vertical polarization lifetime (2.7 +/- 0.5) 10^5 s
- 99 spin flips during 300 s
- Flipping polarization lifetime 240 s.
- Polarization loss by spin decoherence in the horizontal plane? Or is the spin-flip a culprit?
- Crude model ~ $1/(G\beta^2\gamma)^2$ A.Lechrach et al. e-Print: 1201.5773 [hep-ex]
- Low energy protons are preferred
- More experimental scrutiny of spin coherence time of protons is in order, but COSY was decommissioned in 2022
- Plans for dedicated E+B frozen proton spin test ring PTR at CERN (CPEDM Collab)