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".

Fundamental Symmetreis at NICA

(EDM, Axions, Parity and Time-Reversal Violation as Windows to Baryogenesis and Dark Matter)

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N.N.Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna
Institute of Nuclear Research, Troitsk

«Физика фундаментальных взаимодействий»

К 70-летию со дня рождения Валерия Анатольевича Рубакова.

Президиум РАН, Москва, **17 -21 февраля 2025 г.**

After RHIC → SPD@NICA assumes leadership in hafronic collider spin physics for decades to come → it is absolutely imperative to make NICA a versatile spin physics workhorse

- Principal physics goal: gluon helicity in nucleons as an window at the spin crisis in QCD
  A. Arbuzov et al., Prog.Part.Nucl.Phys. 119 (2021), 103858

- Strong need for extension to fundamental symmetries; EDM, axions, parity and T-violation
  Review: S. Vergeles 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

A state of the art in precision spin dynamics in storage rings

(more than a decade of JEDI @ COSY)

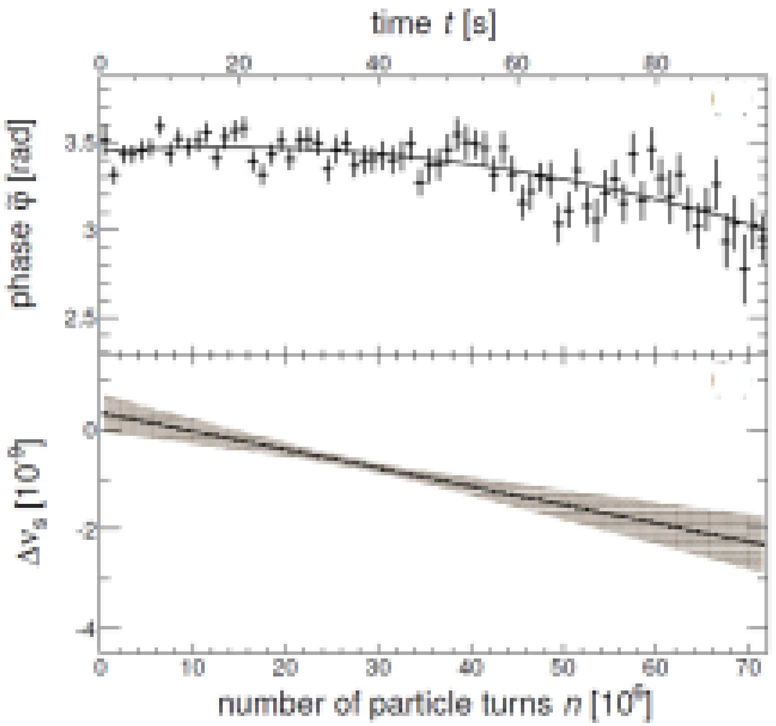
Precision determination of the spin tune [13] II

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:

$$\begin{aligned} \nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n) \end{aligned} \quad (9)$$



Experimental technique allows for:

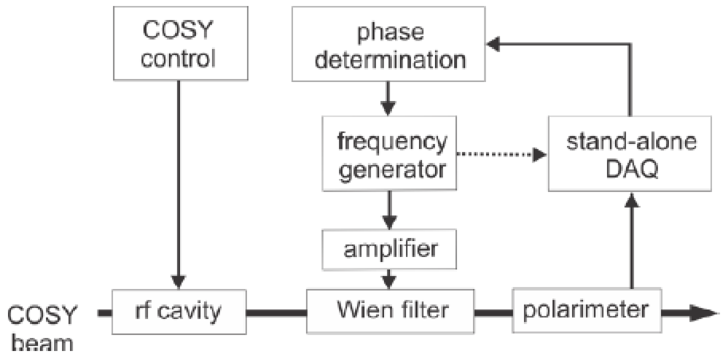
- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.
- $\Rightarrow$ **new precision tool to study systematic effects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

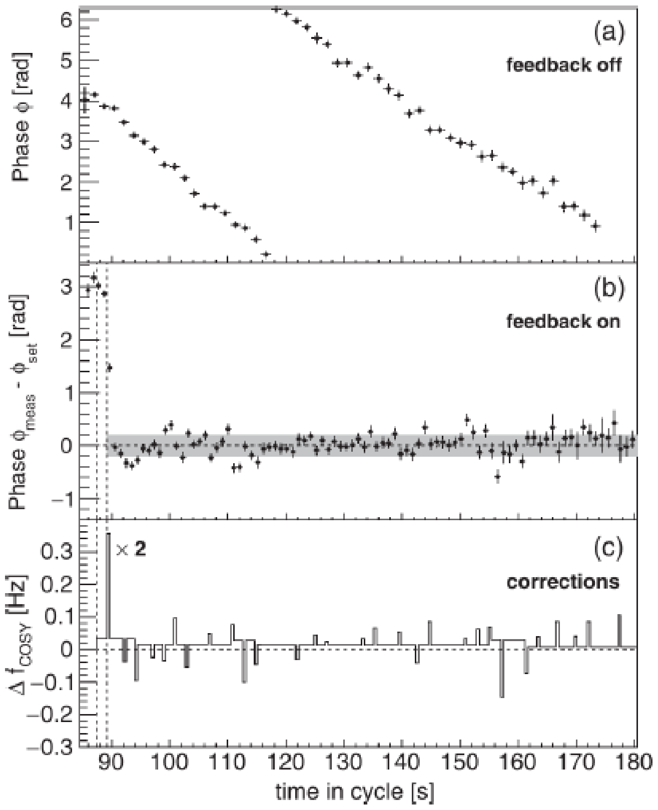
Excellent example of Ramsay's theorem in action

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)

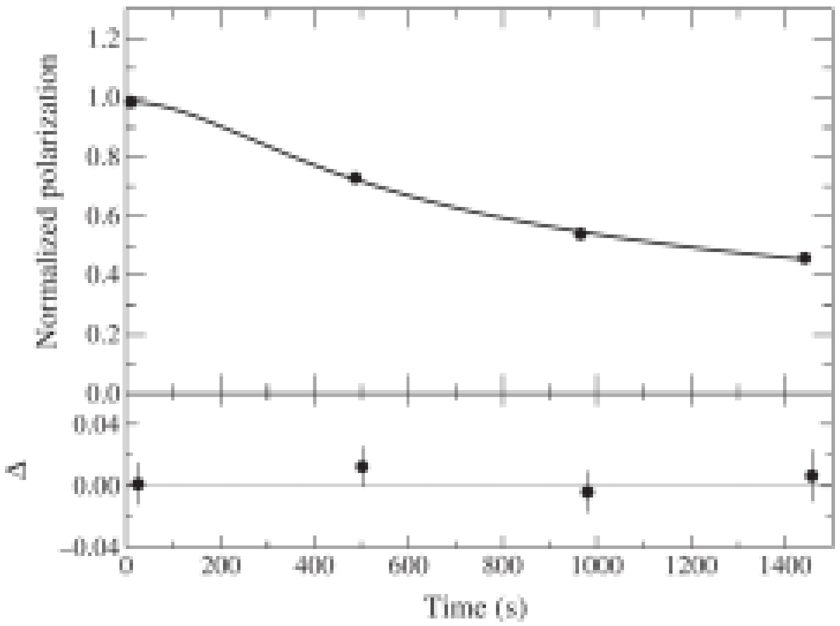




Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ [18].

Optimization of spin-coherence time [12]

Precise adjustments of three sextupole families in the ring



JEDI progress on τ_{SCT}:

$$\tau_{SCT} = (782 \pm 117)\,\mathrm{s}$$

- Previous record: $\tau_{SCT}(\mathrm{VEPP}) \approx 0.5\,\mathrm{s}$ [18] ($\approx 10^7$ spin revolutions).

Stretching SCT by Koop-Shatunov technique of chromaticity minimization

JEDI: routine operation with coherence time of ~ 1500 s

Spring 2015: Way beyond anybody's expectation:

- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (11), since $\sigma_{stat} \propto \tau_{SCT}{}^{-1}$.

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

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 → $-\frac{\hbar}{2f_{(a)}}g_f\partial_\mu a(x)\bar\Psi\gamma^\mu\gamma_5\Psi \qquad m_{(a)} \approx m_\pi\frac{f_\pi}{f_{(a)}}\frac{\sqrt{m_u m_d}}{m_u + m_d}\,,$

Relic axion dark matter

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

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

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

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

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

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

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)

$$\Omega_{\mathrm{res}} = \frac{a_0}{2 f_{(a)}} \frac{v}{c} \gamma \left| g_{\mathrm{f}} G - \kappa_{(a)} \right| \Omega_{\mathrm{c}}$$

is independent of the spin-axion phase difference

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

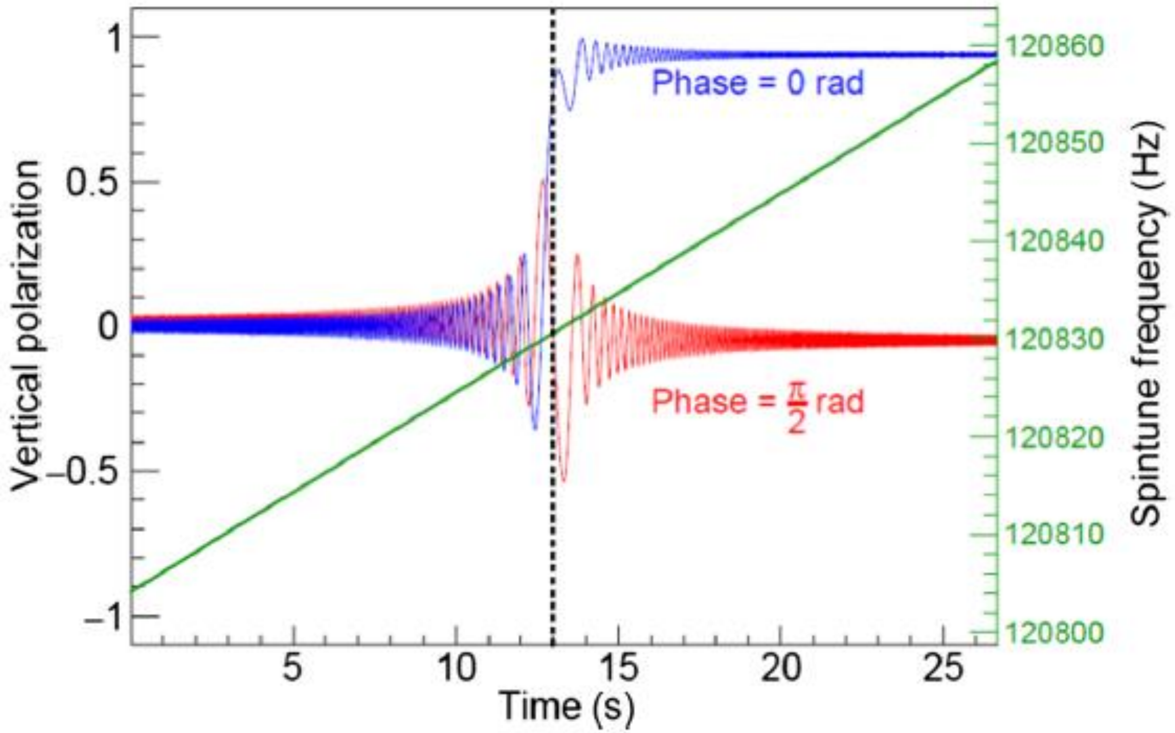
At least 1 s for single determination of the spin phase

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 nemergece of precessing in-plane velocity



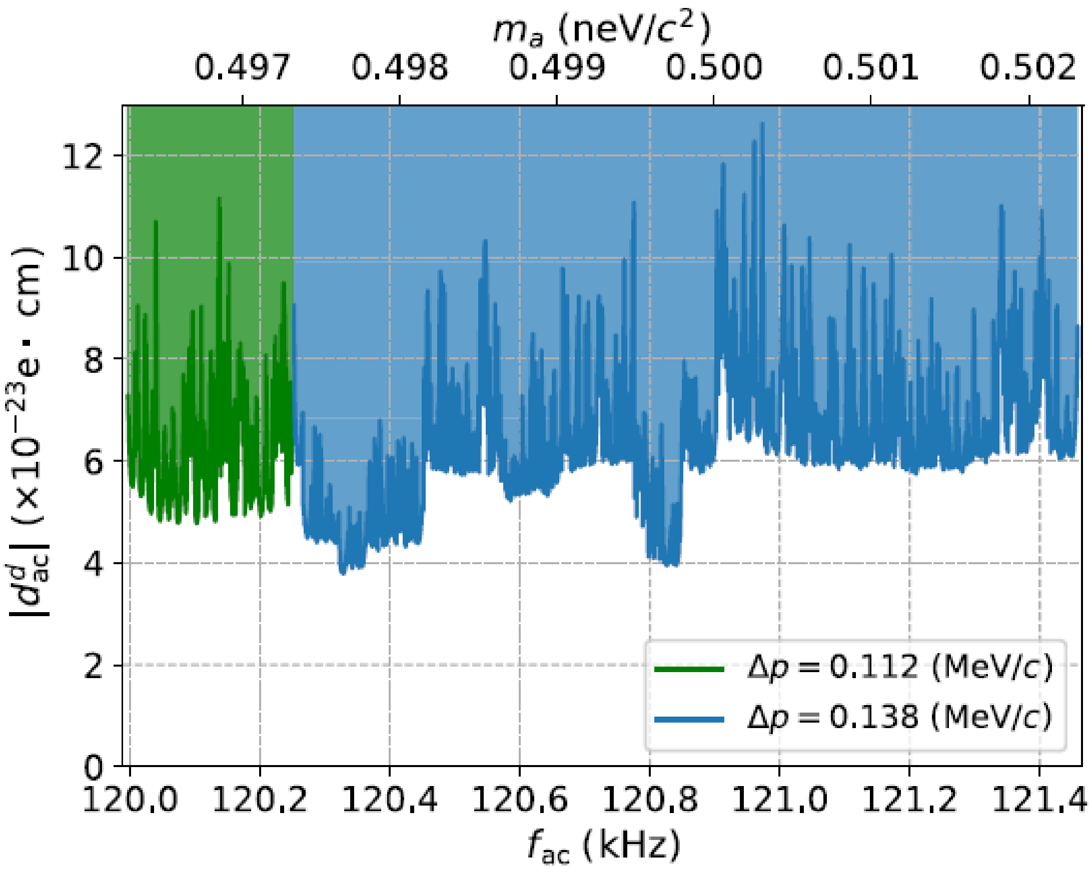
JEDI @ COSY

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

Axions at PTR and NICA facility(Nuclotron and 8-ring) NNN (2022)

PTR (CPEDM): prototype hybrid E+B confinement of 45 MeV frozen spin protons on orbit

Prime motivation: test 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 $$\boldsymbol{\Omega}_s^{\rm mdm} = \frac{q}{m}\left\{-G\boldsymbol{B} + \left(G - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{v}\times\boldsymbol{E}}{c^2}\right\}$$ =0 → zero mass axion antenna

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

Lift the frozen spin condition, but retain the beam momentum and cyclotron frequency (WF regime) $$\Delta \boldsymbol{B} = \frac{1}{v^2}[\boldsymbol{v}\times\Delta\boldsymbol{E}]$$

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 induced rotation of the vertical spin into ring plane, buildup of precessing in-plane polarizatioin

WF regime can well be realized at

- NICA with bypasses
- Modified Nuclotron with extenbded straight sections (Yu.N. Senichev's talk)
- Straight section of the 8-ring as polarization preserving injector to NICA

NICA as a hybrid axion antenna with E+B bypasses

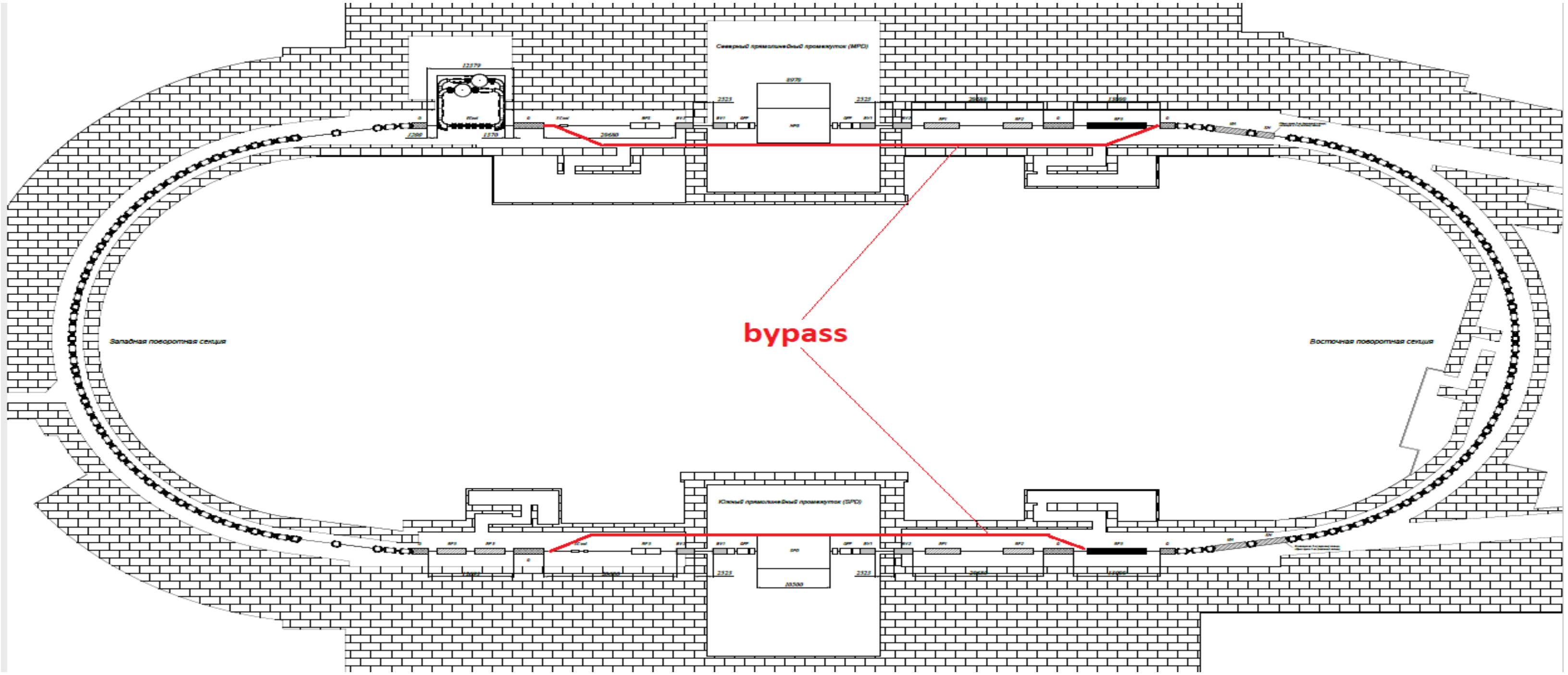
Y. Senichev et al. (2022)
More in Senichev's talk

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
- Proton antenna more sensitive than the deuteron one: larger magnetic moment, lower mass

- Selected references

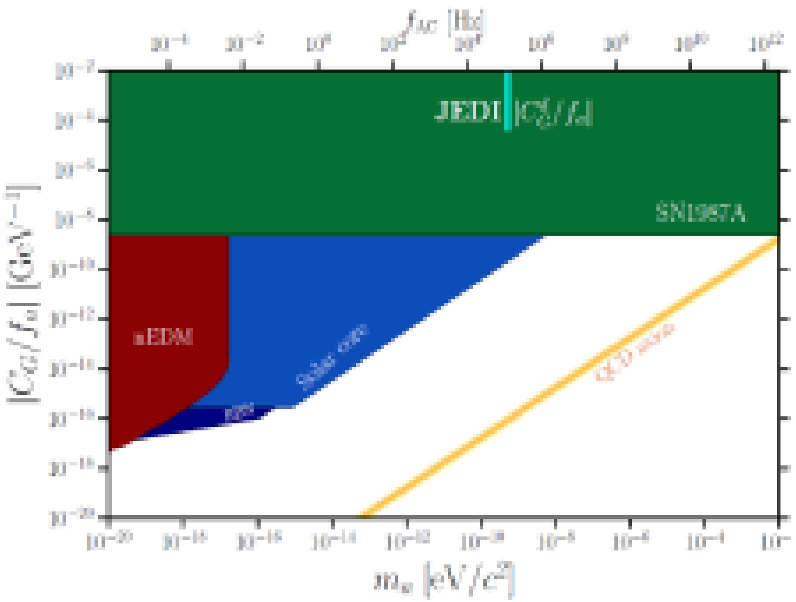
- Classic papers: R.D. Peccei and H.R. Quinn, Phys. Rev. Let., 38, 1440 (1977)
- S. Weinberg, Phys. Rev. Lett. 40, 279 (1978)
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978)
- V. Baluni, Phys. Rev. D., 19, 2227 (1979)
- R.J. Crewther et al., Phys. Lett. B88, 123 (1979), B91, 497 (1980)
- Pseudomagnetic 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
- S. Vergeles, N. Nikolaev, Yu. Obukhov, A. Silenko and O. Teryaev, Physics – Uspekhi, 66(2), 147 (2023) and references therein
- Le Passe-muraille: A.A. Anselm, Sov. J. Nucl. Phys. 42, 936 (1985)
- S.V. Troitsky, JETP Lett. 116 (2022) 11, 767-770
- D.Salnikov et al., JETP Lett.,**117**, 889–897 (2023)
- Supernova axions: N. Bar, K. Blum and G. D'Amico, Phys. Rev. D., 101, 13025 (2020)
- 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)

Summary and outlook

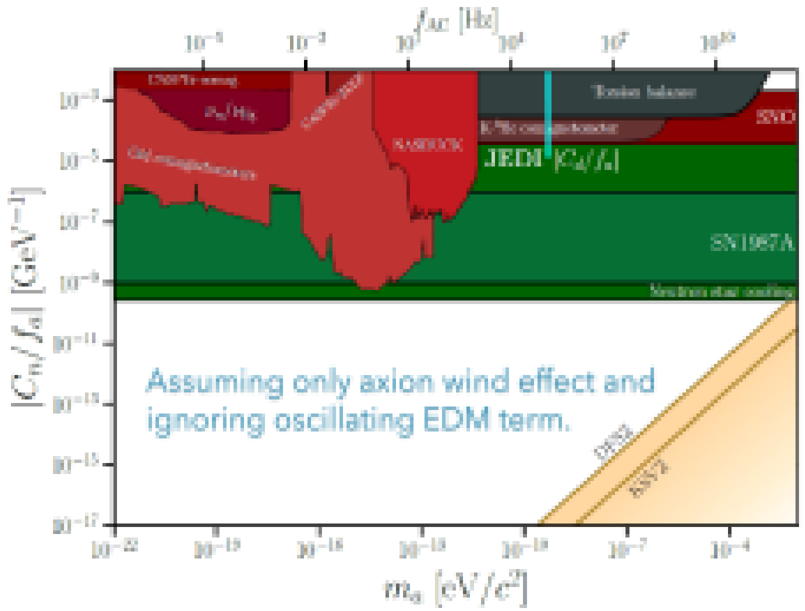
- Any new facility has to have a versatile physics program with multipurpose detectors
- It is imperative to extend the physics program of SPD to novel tests of fundamental symmetries
- Don’t overlok a potential of the external target experiments.

Спасибо за терпение и внимание!

ALP-gluon and ALP-nucleon coupling[3]



ALP-gluon coupling, assuming 100% oscillating EDM.



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

[3]Figures courtesy of C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), https://doi.org/10.5281/zenodo.3932430

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:

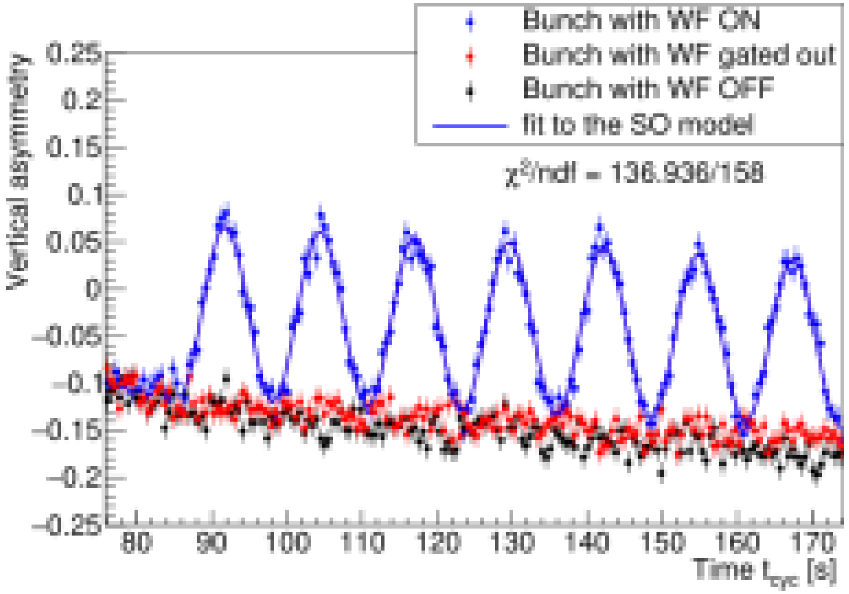
- *Pilot bunch and co-magnetometry of polarized particles stored in a ring* [15]
- *Spin decoherence and off-resonance behavior of radiofrequency-driven spin rotations in storage rings* [16]

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

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, Письма в ЖЭТФ, 118 (2023) 713-720

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

PV expt with single-turn extraction of deuterons from Nuclotron

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 (upgraded Nuclotron to boost intensity)

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

JEDI: the precessing spin phase is measured by time-stamp of oscillating radial polarization : P_x = +/-1 at internal polarimeter within 1-2 s

Time stamp allows single-turn extraction of the bunch of any desired helixity: P_z = +/-1 for PV studies

Fourier anlysis of the PV would reduce systematics

Beam prep & spin-flip & polarimetry & extraction cycle shorter than 5 s → > 5×10^5 cycles per month

No stringent demands for the deuteron beam cooling from the spin coherence time consideration (5 s << 1400 s of JEDI)

Protons might be problematic because of short spin coherence time?

A possibility to run PV expt in Nuclotron parasitically while NICA is busy in the collider mode ?

Modest additions to Nuclotron: RF spin flipper and polarimeter --- they are imperative anyway

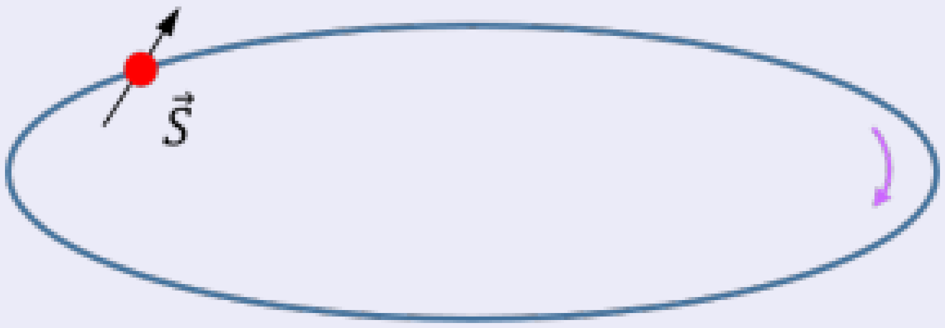
Spin precession of particles with MDM and EDM

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

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: $p(H_2 0)$, 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

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 ?)