Tests of Fundamental Discret Symmetries at NICA Complex

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Parity & T-reversal violation are neither SPD nor MPD expts at NICA proper, but don't miss a chance of outstanding fixed target physics

- They address the issue of fundamental symmetries in the as yet unexplored domain
- They take advantage of storing high intensity beams of polarized protons and deuterons available for the NICA physics
- **Entirely new technique** of the in-the –ring-plane rotating polarization (following e+e- @Budker INP -1987, deuterons JEDI@COSY-2015)
- A feasibility of fast, single turn extraction of beams of any desired spin orientation from Nuclotron or Booster
- Condensed **external** targets offer required **high luminosity**

Talk on behalf of the team of the RFBR grant NICA 18-02-40092 Mega

I.A. Koop, A.I. Milstein, N.N. Nikolaev, A.S. Popov, S.G. Salnikov, P.Yu. Shatunov and Yu.M. Shatunov (PI), PEPAN Letters 17 (2020) 154-157

NICA :

- Search for the single-spin PV in total X-section making use of beams with oscillating helicity (P_z) --- longitudinal polarization without snakes .
- Extraction of judiciously polarized beam onto the external target?
- Search for semistrong T-violation (Okun, Prentki&Veltman, Lee&Wolfenstein) in double-spin (vector x tensor) pd scattering. Polarized deuteron beam on internal ABS polarized hydrogen target.

N. Nikolaev, F. Rathmann, A. Silenko, Yu. Uzikov, arXiv: 2004.09943 [nucl-th]

Forerunners:

- I.B.Vasserman et al., Phys. Lett. B 187 (1987) 172. Record precision of equaity of (g-2) of e+ & e- by comparison of the concurrent in-plane precession of e+ & e- spins. Cornerstone techniques: RF spin flip from vertical to the in-plane one and Koop-Shatunov technique of stretching the lifetime of the in-plane rotating polarization by tuning the chromaticity

- I.M. Sitnik et al., PEPAN Letters No. 2 [111] (2002) (Suggestion to accelerate the in-plane polarized deuterons in Nuclotron)

- Very successful extension to deuterons at COSY (JEDI: PRL 115 (2015) 094801):

Continuous monitoring of the in-plane polarization $P_{x,z}$ by time-stamped up-down asymmetry

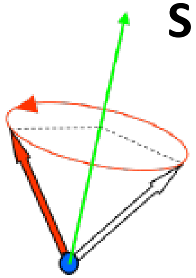
Time spamp and Fourier analysis make the in-plane precessing spin as good as the static one

Spin coherence

Most polarization experiments don't care about coherence of spins along $\vec{n}_s$

Spins aligned:

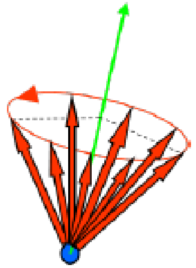
Ensemble *coherent*



Spin stable axis n_s

Spins out of phase:

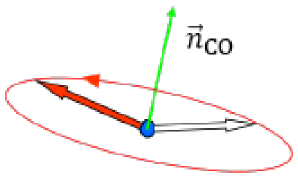
Ensemble *decoherent*



$\Rightarrow$ **Polarization components along $\vec{n}_s$ not affected**

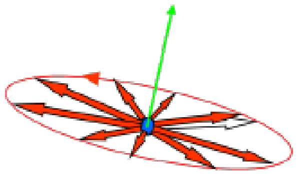
With in-plane spins: $\vec{S} \perp \vec{n}_s$:

Ensemble *coherent*



Over time:

Spins out of phase in horizontal plane



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

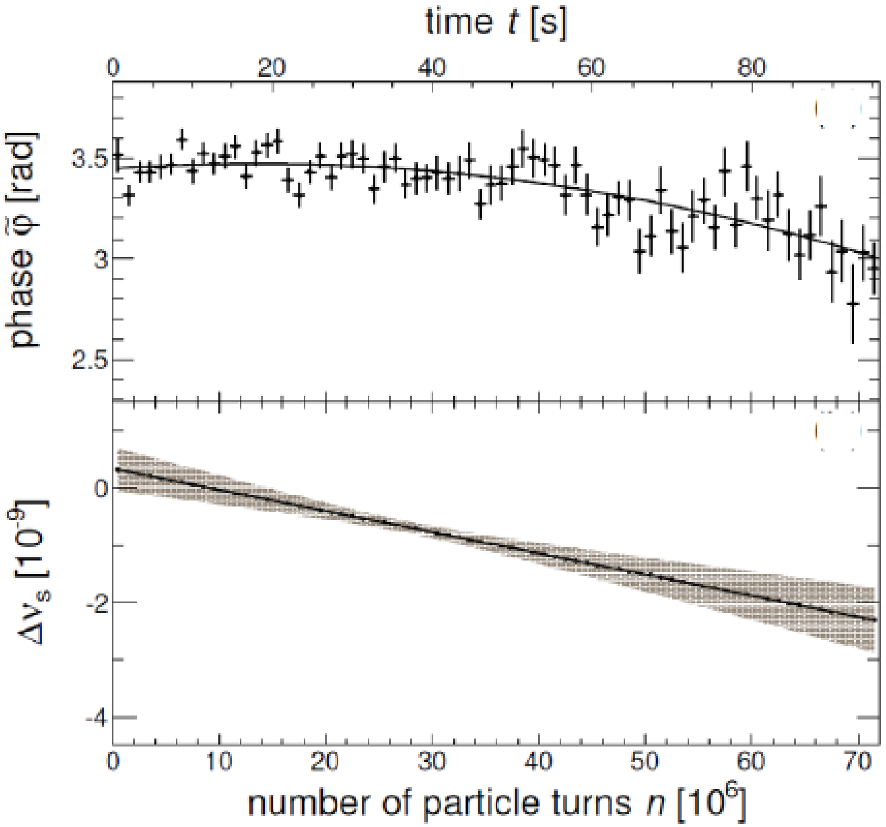
Determination of spin tune [15]

$\theta_s = 2\pi\nu_s$ is spin precession angle per turn,
ν_s is the spin tune

Analyze all time intervals:

- Monitor phase of measured asymmetry with assumed fixed spin tune ν_s^{fix} in a 100 s cycle:

$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{d\tilde{\phi}}{dn} \qquad (6)$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$



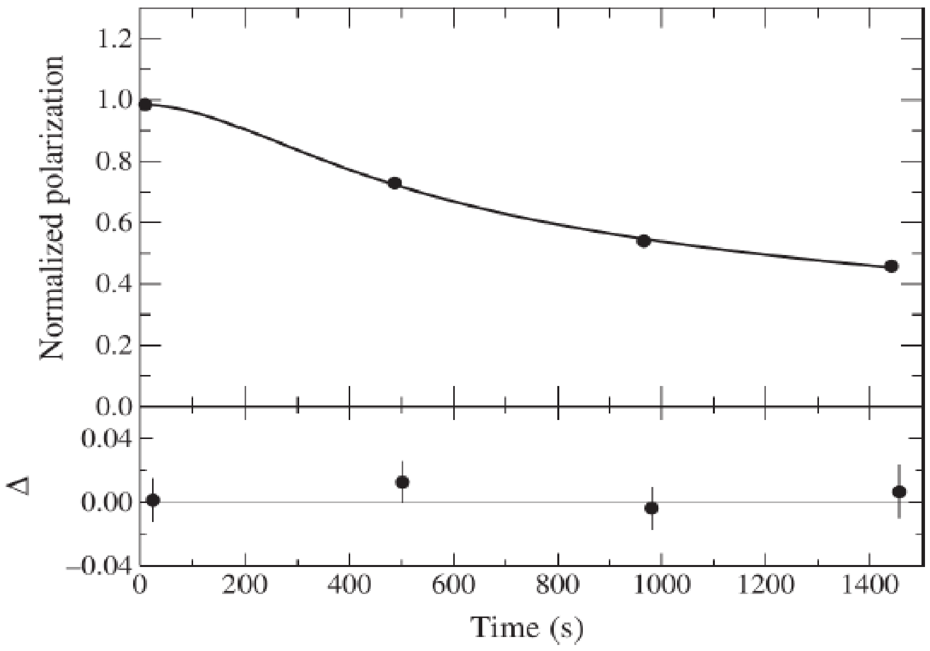
Experimental technique allows for:

- 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.**

Koop-Shatunov technique of fine tuning the chromaticity has successfully been applied to deuterons at COSY

Optimization of spin-coherence time [17]



JEDI progress on τ_{SCT}:

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

- Previous record: $\tau_{SCT}(VEPP) \approx 0.5\,s$ [16] ($\approx 10^7$ spin revolutions).

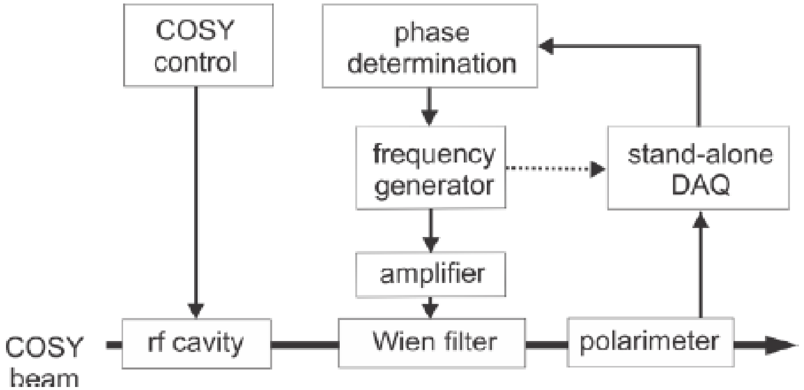
In 2015, way beyond expectation:

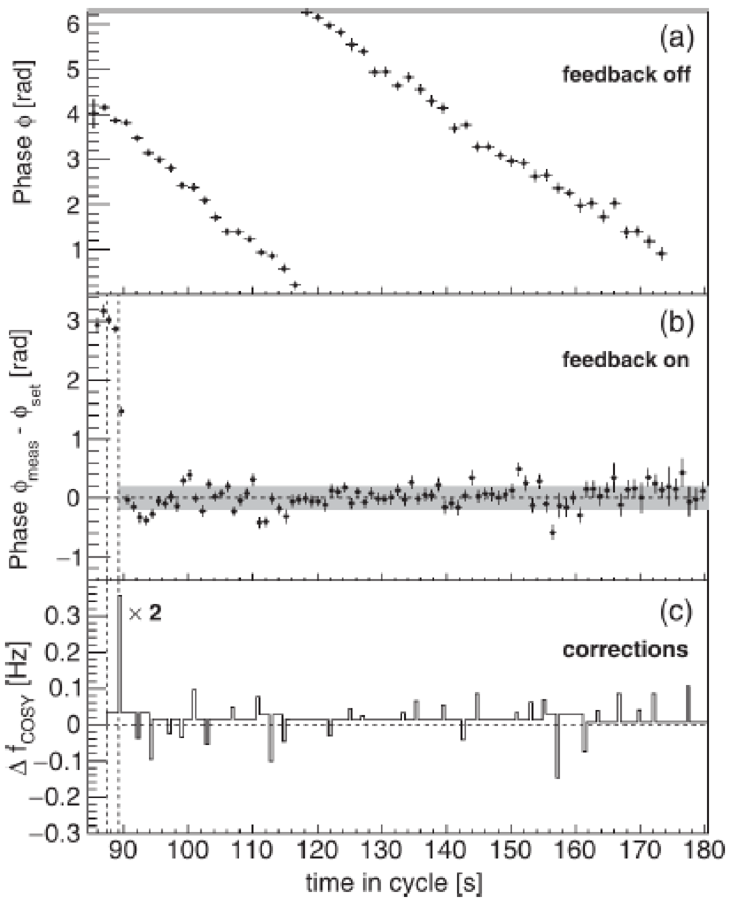
- With about 10^9 stored deuterons.
- Spin decoherence considered one main obstacle of srEDM experiments.

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].

Physics case No. 1: Parity violation (PV) in the SM

A.I. Milstein, N.N. Nikolaev, S.G. Salnikov, *Parity Violation in Proton–Proton Scattering at High Energies*, JETP Letters, 111(4), 197-200 (2020)]; *Несохранение четности в протон дейтронном рассеянии*, Письма в ЖЭТФ, 112 (6), 352-356 (2020), arXiv: 2008.05215

- The conceptually simple observable: PV beam helicity dependence of the total X-section and elastic scattering
- Technical point: very weak PV in the tree level pp-amplitude
- Charge exchange strong radiative corrections to weak charged current interaction generate effective PV neutral current pp interaction
- Absorption corrections to the tree level weak amplitudes are crucial
- Unitarity considerations suggest suppression of PV in inelastic X-section → enhancement of PV in elastic scattering vs. total X-section
- A challenge to experimentalists: the expected asymmetries are few 10^{-8}- 10^{-7}
- On the theory side that's not yet a full story

What is the state of art in PV?

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

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

ANL ZGS: $p(H_2O)$, 5.1 GeV, Nigel Lockyer et al. Phys.Rev. D30 (1084) 860

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

1965: L.Okun; J.Prentki & M.Veltman; T.D.Lee & L.Wolfenstein :

T-odd, P-even and flavor conserving millistrong TVPC interactions as a source of CP violation in kaon decays.

Utterly beyond SM predictions: ~ 10^{-3} T-violation in

EDM of nucleons: $d \sim 10^{-3} \times 10^{-7} \mu_N \sim 10^{-24}$ e cm

β-decays, nuclear γ-transitions, breaking of detailed balance in nuclear reactions,

T-violating spin correlations in double polarized interaction :

n(vector) ^{165}Ho (tensor): $A_{TVPC} < 1.2 \times 10^{-5}$ Huffman et al. PRC 55 (1997) 2684

Can not be induced by initial and final state interactions without explicit T-violation

Intriguing possibility to resolve the baryogenesis puzzle ? (as yet hardly explored by theorists)

Physics case No. 2: search for T-violation at NICA

The conventional method (suggested by **TRIC Collab. for COSY)** : search for TV & PC asymmetry in pd total X-section with vertical vector polarized protons in the ring and tensor polarized deuterons in the ABS target

Error analysis for precessing in-plane polarization: Z. Bagdfsarian et al (JEDI) : Phys.Rev.ST Accel. Beams 17 (2014) no.5, 052803

Potential of $A_{TVPC} < 10^{-6}$, more on that below

Requires a suppression of false signal from stray vector polarization of deuterons to $< 10^{-6}$

Decomposition of the pd total X-section (k = collision axis)

$$\sigma_{\rm tot} = \sigma_0 + \sigma_{\rm TT}\left[\left(\mathbf{P}^{\rm d}\cdot\mathbf{P}^{\rm p}\right) - \left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right)\right]$$ PC TT

$$+\, \sigma_{\rm LL}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma_{\rm T} T_{mn} k_m k_n$$ LL & PC tensor

$$+\, \sigma_{\rm PV}^{\rm p}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma_{\rm PV}^{\rm d}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)$$ PV single spin at NICA

$$+\, \sigma_{\rm PV}^{\rm T}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) T_{mn} k_m k_n$$ PV tensor

$$+\, \sigma_{\rm TVPV}\left(\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]\right)$$ TVPV

TVPC $$+\, \sigma_{\rm TVPC} k_m T_{mn} \epsilon_{nlr} P_l^{\rm p} k_r \,.$$ (TRIC Proposal in Juelich)

$$k_m T_{mn} \epsilon_{nlr} P_l^{\rm p} k_r = T_{xz} P_y^{\rm p} - T_{yz} P_x^{\rm p}$$

Ring with resonance RF solenoid or RF waveguide Wien Filter as a spin rotator

$$\vec{S}(n) = \mathbf{R}_{evol}(n)\vec{S}(0)$$

$$\mathbf{R}_{evol}(n) = \mathbf{R}_{idle}(n)\mathbf{R}_{env}(n) = \begin{pmatrix} \cos\theta_s n \cos\epsilon n & \cos\theta_s n \sin\epsilon n & \sin\theta_s n \\ -\sin\epsilon n & \cos\epsilon n & 0 \\ -\sin\theta_s n \cos\epsilon n & -\sin\theta_s n \sin\epsilon n 0 & \cos\theta_s n \end{pmatrix}$$

$$\theta_s = 2\pi\nu_s \qquad \epsilon = \frac{1}{2}\psi_{RF} \qquad \nu_{res} = \frac{\epsilon}{2\pi} = G\gamma$$

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

vertical radial **PV** longitudinal

,

cos ε n, sin ε n -- the envelopes of polarization. Freezing point $\epsilon n = \frac{\pi}{2}$

Tensor polarization is entirely driven by evolution of the vector polarization

$$\mathbf{Q}(n) = \mathbf{R}_{evol}(n)\mathbf{Q}(0)\mathbf{R}^T_{evol}(n)$$

$$\langle S_{x,z}(0)\rangle = 0 \quad \rightarrow \quad \langle Q_{yx}(0)\rangle, \quad \langle Q_{yz}(0)\rangle, \quad \langle Q_{xz}(0)\rangle = 0$$

$$\langle Q_{yy}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1+3\cos^2\epsilon n]\,,$$

$$\langle Q_{xx}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1+3\sin^2\epsilon n\cos^2\theta_s n]\,,$$

$$\langle Q_{zz}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1+3\sin^2\epsilon n\sin^2\theta_s n]\,,$$ ← $P^P{}_y$ even

$$\langle Q_{yx}(n)\rangle = \tfrac{3}{4}\langle Q_{yy}(0)\rangle\sin 2\epsilon n\cos\theta_s n\,,$$ ← freezes at 0

$$\langle Q_{yz}(n)\rangle = -\tfrac{3}{4}\langle Q_{yy}(0)\rangle\sin 2\epsilon n\sin\theta_s n\,,$$ ← freezes at 0

Unique TVPC → $$\langle Q_{xz}(n)\rangle = -\tfrac{3}{4}\langle Q_{yy}(0)\rangle\sin^2\epsilon n\sin 2\theta_s n\,,$$ ← $P^P{}_y$ odd

Freeze the RF driven rotation at $\epsilon n = \dfrac{\pi}{2}$ → the idle precession shall continue unimpeded, the vertical vector polarization freezes at 0

Are measurements of very small asymmetries feasible?

Counting 10^{15} -10^{16} events is a major challenge. **Measure currents instead?**

Valdau et al. (2016) for TRIC with ABS target at COSY: test stand experiment with Bergoz Fast Current Transformer and Lock-in Amplifier --- the COSY bunches simulated by pulsed current in the wire

Optimistic claim: TVPC asymmetry of 10^{-6} is within the reach of 1 month run

Comparison of +/- polarized beams from different cycles --- systematics ?

Precessing polarization: +/- polarized beams concurrently in the same cycle.

Could one isolate a signal of the time modulated attenuation of the bunch current? The feasibility analysis is in progress.

Repeat the Valdau et al. test stand expt with RF modulated pulses .

P-violation expt with deuteron beam extraction from Nuclotron or Booster?

Feasibility study is in progress

Fast rotation of spin from vertical to the in-plane by RF solenoid

JEDI: the spin phase measured by internal polarimeter within 1-2 seconds

Time stamp: single turn extraction of the bunch with any desired spin orientation

Spin-rotation & polarimetry & extraction cycle can be shorter than 10 s.

No stringent demands for the deuteron beam cooling from the spin coherence time consideration (10 s $\ll$ 1400 s of JEDI)

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

Applications to Electron-Ion Colliders ?

Challenge of polarized DIS at eIC with longitudinally polarized deuterons: a must for the spin structure function of of neutrons

Syberian snakes are beyond question because of impractically large field integral

Ideas on working at the integer spin tune resonance:

Yu. Filatov et al., Phys.Rev.Lett. 124 (2020) 194801; EPJ C80(2020) 778

H. Huang et al., PRAB 23 (2020) 021001

Resort to the precessing longitudinal polarization of deuterons

Oscillating tensor polarizations come along for free

Would it be possible to stretch SCT of 100 GeV deuterons from 1400 s at COSY to 10 h at eRHIC to match the beam storage time ?

Summary:

- Excellent opportunities for fundamental symmetry experiments at the NICA comlpex
- Striking possibility of unambiguous Fourier separation of different spin asymmetries in the total X-section
- P-violation with external target at Nuclotron: asymmetry of 10^{-5} looks feasible in a comparison of consecutive **+/-** spin cycles, thus collecting statistics for 10^{-7} is within the reach of 10000 such twin cycles
- T-violation: feasible at NICA, but requires internal polarized ABS target
- Oscillating longitudinal polarization at eRHIC ?

Many thanks for your patience and attention