Fundamental Symmetries at NICA & COSY:

search for the T- & P-violation with the in-plane polarized deuterons stored in the ring

(отчет по гранту 18-02-40092 Мега НИКА)

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Parity Violation in Proton–Proton Scattering at High Energies

A. I. Milstein[a, b], N. N. Nikolaev[c, *], and S. G. Salnikov[a, b]

JETP Letters, 2020, Vol. 111, No. 4, pp. 197–200.

N.Nikolaev, F. Rathmann, A. Silenko and Yu. Uzikov

arXiv:2004.09943 [nucl-th], under review in Phys. Lett B

NICA SPD Seminar, JINR, 06 July 2020

Outlook:

1. New paradigm: oscillating polarizations instead of the static ones

2. Record achievements of JEDI

3. Yu.M. Shatunov et al. (Budker Inst. + Landau Institute): search for parity violation at NICA (Mega Grant 18-02-40092)

4. Further extension to T-violation in pD scattering: top class physics for NICA

5. Polarized deuterons at Electron-Ion Colliders?

6. NICA: neither MPD nor SPD… still don’t miss a chance

JEDI Revolution-2015: the Fourier analysis makes the in-plane precessing spin as good as the static one

PRL 115, 094801 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

New Method for a Continuous Determination of the Spin Tune in Storage Rings and Implications for Precision Experiments

JEDI: put the polarization in the ring plane and monitor oscillating P_x by time-stamped up-down asymmetry

JEDI achivements (more details in the recent talk by Yuri Senichev):

Record 10^{-10} precision in spin precession frequency

Routine 1000-1400 s coherence time for idly precessing in-plane deuteron spin

Feedback to preserve spin phase stability within 0.2 rad

NICA грант 18-02-40092 Мега
Исследование процессов несохранения четности в рассеянии продольно-поляризованных протонов на дейтроне

Strategies for Probing *P*-Parity Violation in Nuclear Collisions at the NICA Accelerator Facility

I. A. Koop[a, b, c, *], A. I. Milstein[a, b], N. N. Nikolaev[d], A. S. Popov[a, b], S. G. Salnikov[a, b], P. Yu. Shatunov[a, b], and Yu. M. Shatunov[a, b]

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NICA (& COSY):

search for the PV in total X-section making use of the oscillating helicity (P_z)

Все украдено до нас:

Early ideas from 2002

Particles and Nuclei, Letters. 2002. No. 2[111]

PRECESSING DEUTERON POLARIZATION

I. M. Sitnik[1], *V. I. Volkov*, *D. A. Kirillov*, *N. M. Piskunov*, *Yu. A. Plis*

Joint Institute for Nuclear Research, Dubna

The feasibility of the acceleration in the Nuclotron of deuterons polarized in the horizontal plane is considered. This horizontal polarization is named precessing polarization. The effects of the main magnetic field and synchrotron oscillations are included. The precessing polarization is supposed to be used in studying the polarization parameters of the elastic *dp* back-scattering and other experiments.

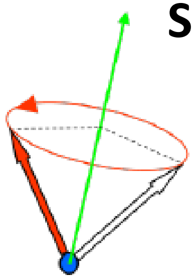
Spin coherence

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

Spins aligned:

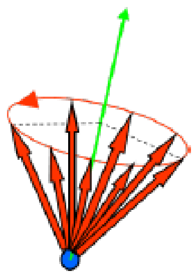
Ensemble *coherent*

Spin stable axis n_s



Spins out of phase:

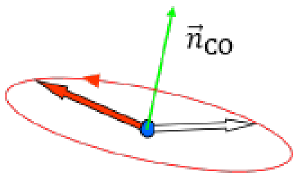
Ensemble *decoherent*



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

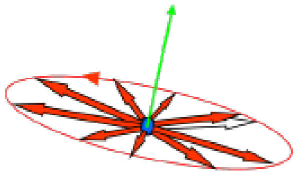
With in-plane spins: $\vec{S} \perp \vec{n}_s$:

Ensemble *coherent*



Over time:

Spins out of phase in horizontal plane



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

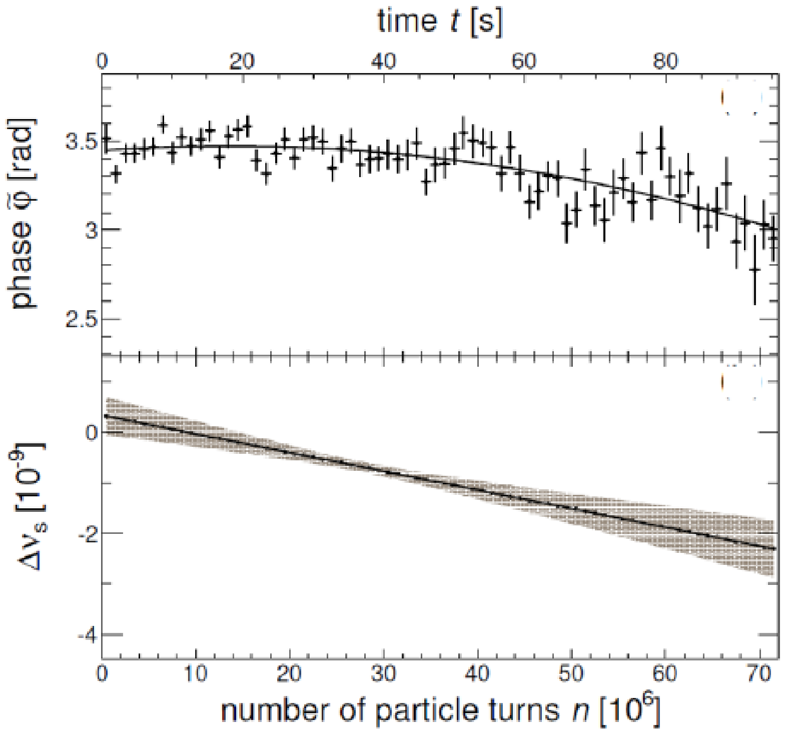
Determination of spin tune [15]

$\theta_S = 2\pi\nu_S$ 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:

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

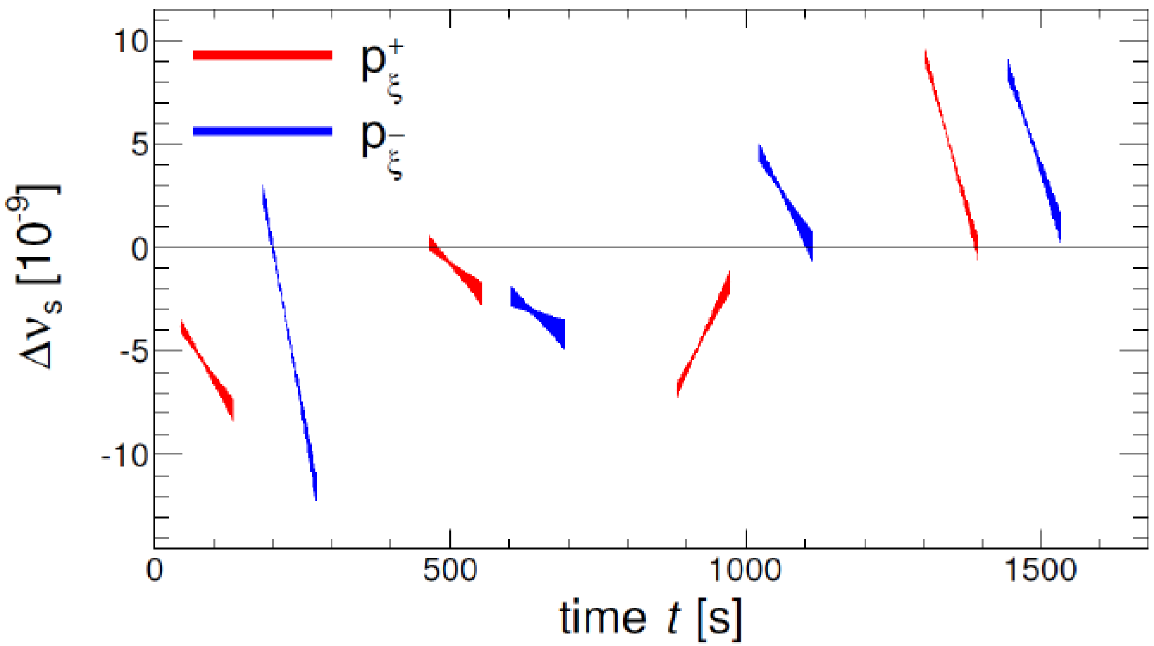


Experimental technique allows for:

- 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.**

Spin tune as a precision tool for accelerator physics

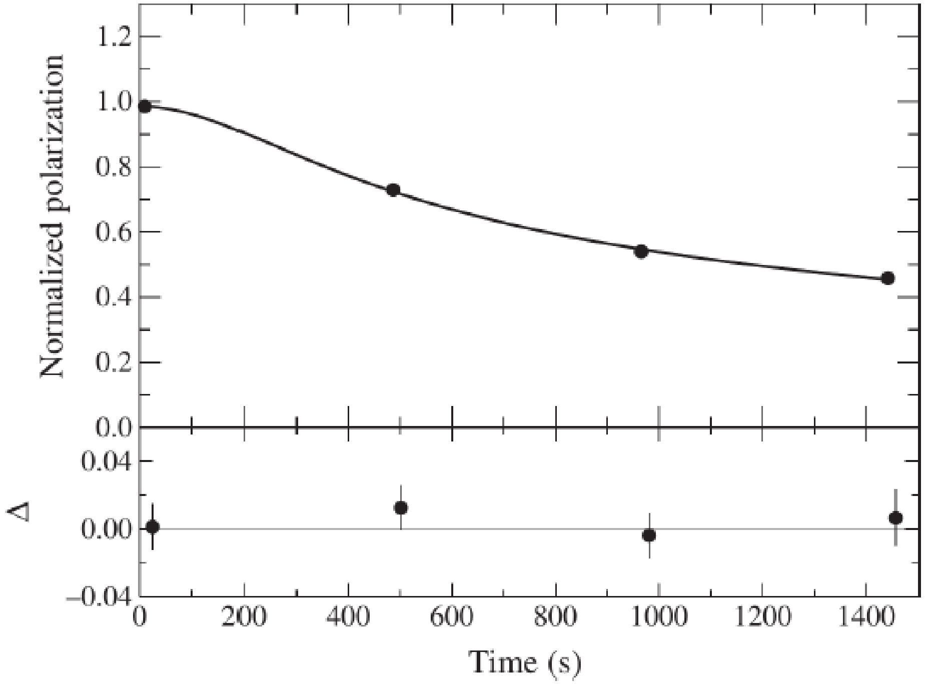


Walk of spin tune ν_s [15].

Applications of new technique:

- Study long term stability of an accelerator.
- Feedback system to stabilize phase of spin precession relative to phase of RF devices (so-called **phase-lock**).
- Studies of machine imperfections.

Optimization of spin-coherence time [17]



JEDI progress on τ_{SCT}:

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

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

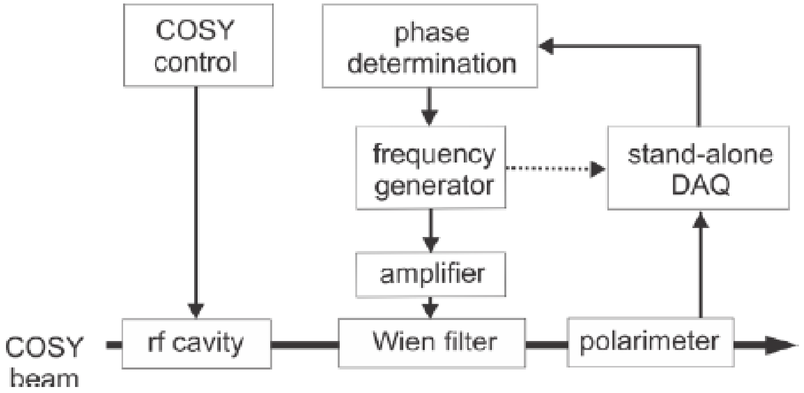
In 2015, way beyond expectation:

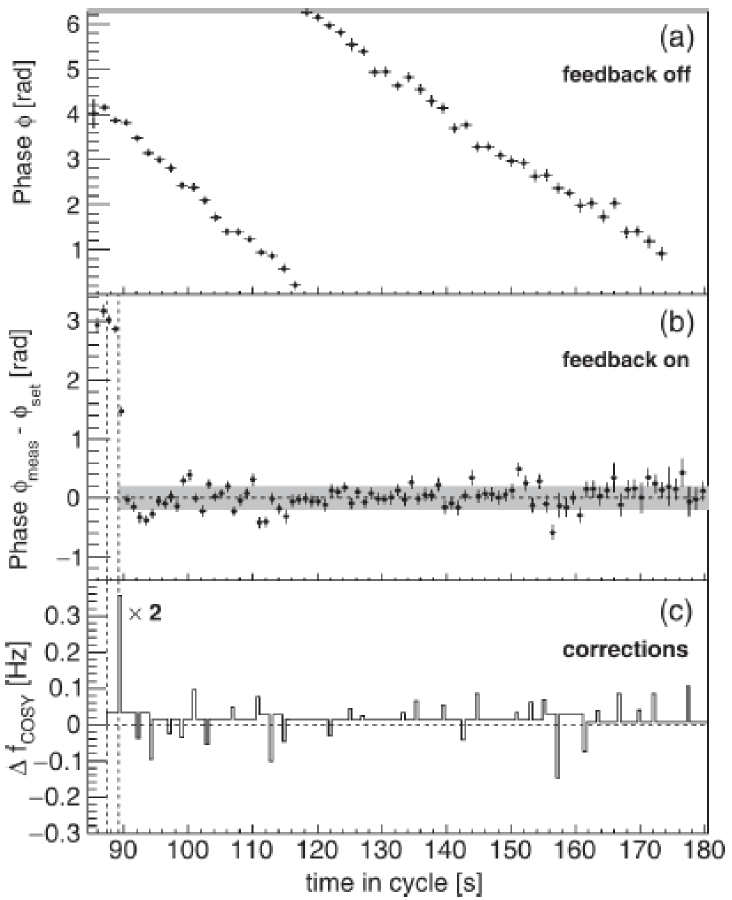
- With about 10^9 stored deuterons.
- Spin decoherence considered one main obstacle of srEDM experiments.

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].

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

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

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

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

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

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

Comprehensive, 35 pages, overview of the theoretical and experimental status of searches of T-violation Beyond Standard Model

SPD -meeting, 5 February, 2018

Search for T-reversal Invariance Violation in Double Polarized pd Scattering

Yuriy Uzikov

JINR, Laboratory of Nuclear Problems

What precision is accessible in pd with internal ABS proton target?

- Polarized ABS proton target density $d=10^{14}$ cm^{-2} atoms
- $t= \pi \times 10^7$ s per 1 year run
- $N = 10^{11}$ deuterons per fill
- dp X-section $\sigma \sim 80$ mb
- Ring frequency f ~ 250 KHz at 250 MeV (v~0.5 c) (f ~ 500 KHz at v~ c)
- $n_{turn} = N\, d\, \sigma \sim 0.8$ events per turn (per 4 microsecond)
- ft ~ 0.8×10^{13} turns per year at $T_d \sim 270$ MeV
- $n_{year} \sim 6 \times 10^{12}$ events at 270 MeV and ~ 10^{13} at T > 1 GeV per 1 year run
- Count all interactions?

Time Reversal Invariance Conservation (TIVOLI): proposal for COSY

The conventional method: search for PVPC asymmetry in total X-section with vertical vector polarized protons in the ring and tensor polarized deuterons in the ABS target

Potential of $A_{TVPC} < 10^{-6}$

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

Need to suppress false signal from vector polarization of deuterons to < 10^{-6}

Parity violation (Koop et al.) : only need unpolarized internal target, 10^{-7} signal is challenging, but not precluded: solid targets are OK

Tensor polarized deuterons: tons of publication from JINR

Decomposition of the pd total X-section

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

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

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

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

$$+ \sigma_{\rm TVPC} k_m T_{mn} \epsilon_{nlr} P_l^{\rm p} k_r\ .$$ TVPC

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

Ring with resonance RF solenoid or WF as a rotator

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

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

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

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

vertical radial longitudinal

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

Tensor polarization is entirely driven by evolution of the vector polarization

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

What do you need at NICA in the pre-SPD era?
Parity violation

1. Major PV signal comes from elastic scattering

A. I. Milstein[a, b], N. N. Nikolaev[c, *], and S. G. Salnikov[a, b]
JETP Letters, 2020, Vol. 111, No. 4, pp. 197–200.

SM expectation: $A_{PV} \sim 10^{-7}$, neutron rich targets are favored by the conventional treatment of weak-strong interference.
Unpolarized solid target is OK

2. Bonn: pp at 45 MeV, several years of running, S. Kystrin et al. PRL 58 (1987) 1616
   $A_{PV} = (1.5 +/- 0.22)\ 10^{-7}$

3. ANL ZGS: $p(H_20)$, 5.1 GeV, N. Lockyer et al. Phys.Rev. D30 (1084) 860
   $A_{PV} = (26.5 +/- 6.0 +/- 3.6\ )\ 10^{-7}$

4. Big detector challenge: 10^{15} interactions in 1 year → recording 10^8 events per second
→ 150 interactions per turn ?
→ Solid target is imperative

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

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

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

$$\langle Q_{zz}(n)\rangle = \tfrac{1}{2}\langle Q_{yy}(0)\rangle[-1 + 3\sin^2 \epsilon n \sin^2 \theta_s n]\,,$$ ← $P^P{}_y$ 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 $\epsilon n = \frac{\pi}{2}$ → the idle precession shall continue unimpeded, the vertical vector polarization freezes at 0

What do you need at NICA in the pre-SPD era? BSM millistrong T-violation

1. Store vertically polarized deuterons, T_{yy} **comes free of charge**

2. **RF solenoid** to rotate the vector polarization into the ring palne

3. Simultaneous generation of **large tensor polarization T_{xz}**

4. **Internal ABS polarized target** (HERMES target serves at COSY, still another PAX target is available at COSY)

5. IUCF: easy manipulation of the proton target vector polarization

6. In-plane tensor polarization precesses at double frequency

7. PV and TVPC signals are trivially separated by continuous Fourier analysis based on time stamp of precession phase

8. What is the systematic background? **None !**

IUCF: beam P and target Q polarizations F. Rathmann *et al.*. Phys.Rev. C58 1998) 658-673

TABLE I. Complete set of Cartesian polarization components of beam and target for the two parts, PRE and POST, of the measuring cycle and the target guide field orientations $\pm x$, $\pm y$, and $\pm z$. The large wanted components of beam and target polarization are shown in boldface. There are unwanted components such as S_{P_y}, S_{Q_x}, and S_{Q_z} that do not flip sign with guide field and those that reverse with guide field in a direction perpendicular to the desired orientation.

	$\pm x$		$\pm y$		$\pm z$	
	PRE	POST	PRE	POST	PRE	POST
P_x	0.0052(47)	0.0089(44)	0.0052(47)	0.0089(44)	0.0052(47)	0.0089(44)
P_y [a]	**0.5801(34)**	**0.5425(32)**	**0.5802(34)**	**0.5417(32)**	**0.5765(34)**	**0.5447(32)**
P_z	−0.0021(47)	0.0003(44)	−0.0021(47)	0.0003(44)	−0.0021(47)	0.0003(44)
Q_x	**0.7401(59)**	**0.7394(56)**	−0.0039(59)	0.0039(56)	−0.0071(23)	−0.0052(23)
Q_y	0.0111(59)	0.0039(56)	**0.7400(59)**	**0.7406(56)**	−0.0055(59)	−0.0034(56)
Q_z	0.0158(60)	0.0240(60)	−0.0174(61)	−0.0121(61)	**0.7401(42)** [b]	**0.7400(40)** [b]
S_{P_y}	−0.0008(18)	−0.0005(17)	−0.0008(18)	0.0005(17)	−0.0008(18)	0.0005(17)
S_{Q_x}	0.0017(23)	−0.0007(23)	−0.0040(23)	−0.0031(23)	−0.0043(23)	−0.0024(23)
S_{Q_z}	−0.0091(82)	−0.0162(82)	−0.0177(82)	−0.0197(82)	0.0013(82)	−0.0086(82)

Beyond SM T-violating, P-violating & flavor conserving interaction

Enormous theoretical activity: J.de Vries, **E. Epelbaum**, L. Girlanda, A. Gnech, E. Mereghetti and M. Viviani, to be publ. in Frontiers in Physics, arXiv:2001.09050 [nucl-th], 68 p., 239 refs.

TVPV: crossed proton and deuteron vector polarizations

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

Oscillating horizontal deuteron polarization, vertical proton polarization

$$\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]=P_x^{\rm d}(n)\,P_y^{\rm p}\propto P_y^{\rm p}\,\sin\epsilon n^{*}\cdot\cos\theta_s n$$

Vertical deuteron polarization, radial proton polarization

$$\sigma_{\rm TVPV}\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]\propto P_y^{\rm d}(0)\,P_x^{\rm p}\cos\epsilon n\,,$$

Invoke still another Fourier marker: longitudinal “guide” B-field → oscillating radial & vertical proton polarization ?

Precessing transverse polarization in the target cell as a tool to better isolate the TVPV signal from PC TT asymmetry

Ω_T - precession of the target polarization about the guide B_z

$$\Delta\sigma/[\sigma P^d(0) P^p(0)] = A_{TT} \cos \varepsilon n \quad \cos \Omega_T n$$
$$+ A_{TVPV} \cos \varepsilon n \; \sin \Omega_T n$$
$$+ A_{TT} \sin \varepsilon n \; \sin \Omega_T n \cos \theta_S n$$
$$+ A_{TVPV} \sin \varepsilon n \; \cos \Omega_T n \cos \theta_S n$$

Good cross check: 4 amplitudes can be determined, only 2 are independent

Bold speculations on eRHIC

Challenge of polarized DIS at eRHIC with longitudinally polarized deuterons

Syberian snakes are beyond question because of impractically large field integrals

Ideas on working at the integer spin tune resonance: NICA V. Kondratenko & Y. Filatov ..

EIC H. Huang, F. Méot, V. Ptitsyn, V. Ranjbar, and T. Roser, Phys. Rev. Accel. Beams **23**, 021001 (2020).

Have a look at precessing longitudinal polarization of deuterons?

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:

- New paradigm of precession horizontal polarization
- Simple description of the RF driven evolution of the tensor polarization of injected vertically polarized deuterons
- Striking possibility of unambiguous Fourier separation of different components of the total X-section
- Concurrent measurement in the same setup of the whole family of single and double spin observables
- Fresh look at TRIC/TIVOLI: COSY, NICA,…
- Worthwhile to dream of oscillating longitudinal polarization at eRHIC

Many thanks for your patience and attention

Precessing polarization at NICA

Store certically polarized deuterons, T_{yy} comes free of charge

RF solenoid to rotate the vector polarization into the ring palne

Simultaneous generation of large tensor polarization T_{xz}

Internal ABS polarized target (HERMES target serves at COSY, still another PAX target is available at COSY)

IUCF: easy manipulation of the target polarization.

Unpolarized solid (carbon?) target for PV experiment

In-plane deuteron vector polarization precesses at ~ 50-150 KHz

In-plane tensor polarization precesses at double frequency

PV and TVPC signals are trivially separated by continuous Fourier analysis based on time stamp of precession phase

What is the systematic background? **None !**