



# New approach to search for parity-even and parity-odd time-reversal violation beyond the Standard Model in a storage ring



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## ABSTRACT

Time-reversal breaking and parity-conserving millistrong interactions, suggested in 1965, still remain a viable mechanism of CP-violation beyond the Standard Model. One of its possible manifestations is the T-odd asymmetry in the transmission of tensor-polarized deuterons through a vector-polarized hydrogen gas target. Upon the rotation of the deuteron polarization from the vertical direction into the ring plane, the T-odd asymmetries, odd against the reversal of the proton polarization in the target, will continuously oscillate with first or second harmonics of the spin precession frequency. The Fourier analysis of the oscillating T-odd asymmetries allows for an easy separation from background persistent in conventional experiments employing static vector and tensor polarizations.

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## 1. Introduction

In 1965 Okun [1], Prentki & Veltman [2], and Lee & Wolfenstein [3] suggested millistrong, flavor and parity (P) conserving, but time-reversal (T) violating (TVPC) interactions, as a source of CP violation in neutral kaon decays. The Standard Model (SM) predicts the experimentally accessible CP violation only in flavor changing processes. In beyond SM (BSM) millistrong CP-odd interactions (MSCPV), T-violation in flavor conserving strong and nuclear reactions,  $\gamma$ -transitions and  $\beta$ -decays is possible at the level of  $\sim 10^{-3}$ . An intriguing open issue is whether MSCPV can resolve the puzzle of the anomalously large baryon asymmetry of the Universe (for a review, see [4]).

In this paper, we propose a new approach to the search for T-violation in double-polarized proton-deuteron ( $pd$ ) transmission experiments. It is based on the rotation of the vertical polarization of stored deuterons into the ring plane. The in-plane vector and tensor polarizations precess with the first or second har-

monic of the idle spin-precession frequency. Their interactions with an internal polarized hydrogen target give rise to a hierarchy of polarization asymmetries. In the conventional search for T-violation in double-polarized  $pd$  interactions [5,6], the static T-odd tensor asymmetry receives a systematic contribution from the hard-to-control background from vector polarized deuterons in the tensor polarized cell target [7,8] (for a discussion of unwanted spin components in cell targets, see [9]). It is crucial that this daunting task of separating the T-violating signal from the systematic background, can be met with Fourier analyses, which readily distinguishes different polarization asymmetries by their oscillation frequency and parity with respect to the reversal of the proton target polarization. This feature gives storage ring experiments with oscillating in-plane polarizations a clear advantage over experiments with static deuteron and proton polarizations.

As a proof-of-principle, in 2014 the JEDI collaboration for the first time made use of the precessing in-plane deuteron polarization for a high precision measurement of the spin-precession frequency [10,11]. Subsequently, a feedback system to stabilize the spin-precession frequency was developed [12]. The possibility of

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fast reversal and rotation of the proton target polarization has been demonstrated, e.g., at IUCF [9]. Putting the oscillating polarization of stored protons to use in the search for P-violation in hadronic interactions at the NICA collider has recently been proposed in [13]. The possibility to accelerate particles with precessing polarization has already been discussed in 2002 [14].

Our focus here will be on search for the MSCPV interaction via the TVPC asymmetry in the total cross section of double-polarized proton-deuteron ( $pd$ ) scattering. Alongside the TVPC asymmetry, one can study in the same experimental setup the T-odd and P-odd (TVPV) asymmetry, which recently received much theoretical scrutiny (for an extensive discussion, see [15,16]). We show that, besides these two T-odd asymmetries, oscillating vector and tensor polarizations provide a new access to a whole family of further single- and double-polarization observables.

In the SM, flavor-conserving TVPC effects are only possible to the second order in weak interactions, and are far below the reach of present experimental observations. An example of the second order observable is the much discussed TVPV electric dipole moment of the neutron, expected in the SM at the level of  $d_n \sim 10^{-32}$  e cm [17]. The dimensional estimate from MSCPV amounts to  $d_n \sim 10^{-24}$  e cm [18–21]. The best recent experimental upper bound is  $d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \cdot 10^{-26}$  e cm [22]. However, in view of the complexity of the interplay of long-distance and short-distance effects, the present bounds on  $d_n$  do not preclude MSCPV as a source of CP-violation [23,24].

Direct constraints on TVPC effects in flavor-conserving processes include tests of the detailed-balance principle [25], studies of the  $\beta$ -decay of polarized neutrons [26], transmission of polarized neutrons through a spin-aligned  $^{165}\text{Ho}$  target [27], and charge-symmetry breaking in spin observables of  $pn$  scattering [28]. According to [23,24], these bounds do not contradict expectations from the MSCPV interaction, and Kurylov et al. strongly emphasize the importance of direct searches for TVPC effects in scattering experiments [23].

In transmission experiments, the best upper bound on the TVPC asymmetry has been achieved in interactions of 5.9 MeV polarized neutrons with tensor polarized  $^{165}\text{Ho}$  crystals, yielding  $A_{\text{TVPC}} = A_5 < 2.2 \cdot 10^{-5}$  [27]. The subsequent proposal to search for the TVPC asymmetry in  $pd$ -scattering anticipated interactions of vertically polarized protons, stored in the COSY ring, passing through a tensor-polarized deuterium storage cell target [5]. The related theoretical estimates were performed for the energy range 100 to 1000 MeV [29–31]. On a statistical basis, the TVPC asymmetry of  $\sim 10^{-6}$  is within the reach of  $pd$  transmission experiments [5] (see also [10] for the related discussion of oscillating asymmetries). Experimental investigations of the T-invariance in  $pp$  scattering were conducted, probing the equality of the final state polarization  $P$  and the vector analyzing power  $A$ . A relatively weak bound on  $(P - A)$  was obtained, the best result being  $(P - A) = 0.0047 \pm 0.0025_{\text{stat}} \pm 0.0015_{\text{sys}}$  [32]. With the null observable available in double-polarized  $pd$  scattering, there is a potential to further tighten the upper bound on T-violation in nucleon-nucleon interactions by several orders in magnitude.

The further presentation is organized as follows. We start with a brief review of spin observables in  $pd$  transmission experiments. Then, we derive the evolution equation of vector and tensor polarizations of deuterons when exposed to a resonant RF spin rotator, and report on explicit solutions for the precessing vector and tensor polarizations for the relevant initial vertical polarization. Next, we discuss how Fourier analyses furnish the determination of TVPC and TVPV asymmetries, and comment on the access to further spin observables, beyond the T-violating ones, using precessing polarizations.

## 2. Spin asymmetries in the total $pd$ cross section

The spin-dependent total  $pd$  cross section is written as

$$\begin{aligned} \sigma_{\text{tot}} = & \sigma_0 + \sigma_{\text{TT}} \left[ \left( \mathbf{P}^d \cdot \mathbf{P}^p \right) - \left( \mathbf{P}^d \cdot \mathbf{k} \right) \left( \mathbf{P}^p \cdot \mathbf{k} \right) \right] \\ & + \sigma_{\text{LL}} \left( \mathbf{P}^d \cdot \mathbf{k} \right) \left( \mathbf{P}^p \cdot \mathbf{k} \right) + \sigma_{\text{T}} T_{mn} k_m k_n \\ & + \sigma_{\text{PV}}^p \left( \mathbf{P}^p \cdot \mathbf{k} \right) + \sigma_{\text{PV}}^d \left( \mathbf{P}^d \cdot \mathbf{k} \right) \\ & + \sigma_{\text{PV}}^T \left( \mathbf{P}^p \cdot \mathbf{k} \right) T_{mn} k_m k_n \\ & + \sigma_{\text{TVPV}} \left( \mathbf{k} \cdot \left[ \mathbf{P}^d \times \mathbf{P}^p \right] \right) \\ & + \sigma_{\text{TVPC}} k_m T_{mn} \epsilon_{nlr} P_l^p k_r. \end{aligned} \quad (1)$$

Here  $\mathbf{P}^d$  and  $\mathbf{P}^p$  are the vector polarizations of deuteron and proton,  $T_{mn}$  is the tensor polarization of the deuteron and  $\mathbf{k}$  is the unit vector along the collision axis. We chose the latter for the  $z$ -axis, the  $y$ -axis is orthogonal to the ring plane, so that  $T_{mn} k_m k_n = T_{zz}$ , and

$$k_m T_{mn} \epsilon_{nlr} P_l^p k_r = T_{xz} P_y^p - T_{yz} P_x^p. \quad (2)$$

In Eq. (1), the cross sections  $\sigma_0$ ,  $\sigma_{\text{TT}}$ ,  $\sigma_{\text{LL}}$ , and  $\sigma_{\text{T}}$  correspond to ordinary P-even and T-even interactions,  $\sigma_{\text{PV}}^p$ ,  $\sigma_{\text{PV}}^d$ , and  $\sigma_{\text{PV}}^T$  are signals of the P-violation, and  $\sigma_{\text{TVPV}}$  denotes the T- and P-violating one.

The last term in Eq. (1),  $\sigma_{\text{TVPC}}$ , denotes the null observable for the TVPC interaction [33–35]. This observable can be neither imitated by initial, nor by final state interactions; it would vanish unless the manifest T-violating interaction is at work.

The TVPC and TVPV experiment with polarized deuterons in a storage ring with installed RF spin rotator is envisaged as follows. One starts with injection of deuterons with vertical spin  $\vec{S}$  and tuning conditions to provide a long spin-coherence time [36,37]. Throughout this paper,  $\vec{S}(t)$  will stand for the time-dependent deuteron spin operator, its expectation value,  $\vec{P}^d(t) = \langle \vec{S}(t) \rangle$ , is the polarization vector. The initial vertical vector polarization  $\langle S(0) \rangle = P_y^d(0) \vec{e}_y$  entails also the tensor polarization  $T_{yy}(0) = \langle Q_{yy}(0) \rangle$ , where the spin-tensor operator is defined as

$$Q_{mn}(t) = S_m(t) S_n(t) + S_m(t) S_m(t) - \frac{2}{3} \vec{S}^2 \delta_{mn}. \quad (3)$$

The electric quadrupole moment of the deuteron is of the order of the deuteron magnetic moment times the size of the deuteron. In a storage ring, its interaction with the gradient of the motional electric field [38] is some 13 to 14 orders in magnitude smaller than the interaction of the magnetic moment with the magnetic field. Consequently, the deuteron spin dynamics in a storage ring is entirely driven by the evolution of its vector polarization.

The angular velocity  $\vec{\Omega}$  of the idle spin precession in the laboratory frame is given by the Thomas-Bargmann-Michel-Telegdi (T-BMT) equation [39]. It is convenient to follow rotations of the spin with respect to the particle momentum, i.e.,  $\vec{\Omega}_s = \vec{\Omega} - \vec{\Omega}_r$ , subtracting the cyclotron angular velocity  $\vec{\Omega}_r$ . A convenient quantity is the spin tune  $\nu_s = \Omega_s / \Omega_r$ . The idle spin-precession angle per turn equals  $\theta_s = 2\pi \nu_s$ . As a spin rotator, we consider an RF solenoid with magnetic field along the  $z$ -axis, tangential to the beam orbit. It is operated at the spin-precession frequency  $f_s = \Omega_s / (2\pi) = \nu_s f_r$  (modulo to integers of the cyclotron frequency  $f_r$ ).

As a function of the turn number  $n$ , the spin evolves stroboscopically: (1) it idly precesses about the vertical axis during a full revolution, and (2), while passing the RF solenoid, it acquires a turn-dependent rotation about the  $z$ -axis by the angle  $\psi(n) = \psi_{\text{RF}} \cos(\theta_s n)$ ,  $\psi_{\text{RF}} \ll 1$ . The polarimeter, located right behind the spin rotator, stroboscopically analyses the spin orientation

once per turn. The RF spin rotator gives rise to the evolution of the envelope of the precessing polarization. The transition from the stroboscopic evolution to the continuous time dependence with  $n = f_r t$  is furnished by the Bogoliubov-Krylov-Mitropolsky (BKM) averaging [40].

Following the treatment described in [41], extended to the **SO(3)** formalism, one can derive the BKM-averaged spin evolution in factorized form,

$$\vec{S}(n) = \mathbf{R}_{\text{evol}}(n) \vec{S}(0), \quad (4)$$

$$\mathbf{R}_{\text{evol}}(n) = \mathbf{R}_{\text{idle}}(n) \mathbf{R}_{\text{env}}(n),$$

where the idle precession and the spin-envelope evolution matrices equal, respectively,

$$\mathbf{R}_{\text{idle}}(n) = \begin{pmatrix} \cos \theta_s n & 0 & \sin \theta_s n \\ 0 & 1 & 0 \\ -\sin \theta_s n & 0 & \cos \theta_s n \end{pmatrix}, \quad (5)$$

$$\mathbf{R}_{\text{env}}(n) = \begin{pmatrix} \cos \epsilon n & \sin \epsilon n & 0 \\ -\sin \epsilon n & \cos \epsilon n & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (6)$$

The latter describes the rotation of the spin envelope in the  $xy$ -plane by a constant angle  $\epsilon = \psi_{\text{RF}}/2$  per turn, *i.e.*, with the spin-resonance tune (strength)  $\nu_{\text{res}} = \epsilon/(2\pi)$ . Then, the final spin-evolution operator becomes

$$\mathbf{R}_{\text{evol}}(n) = \begin{pmatrix} \cos \theta_s n \cdot \cos \epsilon n & \cos \theta_s n \cdot \sin \epsilon n & \sin \theta_s n \\ -\sin \epsilon n & \cos \epsilon n & 0 \\ -\sin \theta_s n \cdot \cos \epsilon n & -\sin \theta_s n \cdot \sin \epsilon n & \cos \theta_s n \end{pmatrix}. \quad (7)$$

At the boundary condition  $\langle \vec{S}(0) \rangle = P_y^d(0) \vec{e}_y$  one has

$$\vec{S}(n) = S_y(0) [\cos(\epsilon n) \vec{e}_y + \sin(\epsilon n) [\cos(\theta_s n) \vec{e}_x - \sin(\theta_s n) \vec{e}_z], \quad (8)$$

with the conspicuous interpretation of  $\cos \epsilon n$  and  $\sin \epsilon n$  being the envelopes of the vertical and in-plane polarizations, respectively. Apart from the time dependence of the envelope, the in-plane polarization continuously precesses with the idle precession frequency.

The idle precession frequency  $f_s$  and the spin phase can be determined from the up-down asymmetry, measured in elastic scattering of deuterons on carbon target in the polarimeter [10]. Such a determination of the spin phase from the radial polarization is tantamount to setting the time stamp of the longitudinal polarization.

The interaction of protons of about 135 MeV with a deuterium target [5,6] amounts to the interaction of deuterons of 270 MeV with a proton target, incidentally close to the optimum energy for the polarimetry of deuterons, elastically scattered off a carbon target [42].

### 3. Precessing tensor polarization of the deuteron

As stated above, the spin-tensor operator does not enter per se the spin-interaction Hamiltonian. For that reason, its evolution can be written down right away,

$$\mathbf{Q}(n) = \mathbf{R}_{\text{evol}}(n) \mathbf{Q}(0) \mathbf{R}_{\text{evol}}^T(n), \quad (9)$$

without the need to solve a set of five differential equations for the tensor polarization operator [43–45]. Upon averaging over the injected ensemble of vertically polarized particles, one obtains

$$P_{x,z}^d(0) = \langle S_{x,z}(0) \rangle = 0, \quad (10)$$

although the in-plane polarizations do build up under the action of the spin rotator [see Eq. (8)]. On exactly the same footing, all the off-diagonal tensor polarizations vanish as well,  $T_{yx}(0) = T_{yz}(0) = T_{xz}(0) = 0$ , and  $T_{xx}(0) = T_{zz}(0) = -\frac{1}{2} T_{yy}(0)$ . Then, Eq. (9) yields

$$\begin{aligned} T_{yy}(n) &= \frac{1}{2} T_{yy}(0) \cdot \left[ -1 + 3 \cos^2 \epsilon n \right], \\ T_{xx}(n) &= \frac{1}{2} T_{yy}(0) \cdot \left[ -1 + 3 \sin^2 \epsilon n \cdot \cos^2 \theta_s n \right], \\ T_{zz}(n) &= \frac{1}{2} T_{yy}(0) \cdot \left[ -1 + 3 \sin^2 \epsilon n \cdot \sin^2 \theta_s n \right], \\ T_{yx}(n) &= \frac{3}{2} T_{yy}(0) \cdot \sin \epsilon n \cdot \cos \epsilon n \cdot \cos \theta_s n, \\ T_{yz}(n) &= -\frac{3}{2} T_{yy}(0) \cdot \sin \epsilon n \cdot \cos \epsilon n \cdot \sin \theta_s n, \\ T_{xz}(n) &= -\frac{3}{4} T_{yy}(0) \cdot \sin^2 \epsilon n \cdot \sin 2\theta_s n. \end{aligned} \quad (11)$$

The working point of the experiment, with the vector polarization in the ring plane, is reached at  $n = n^*$ , *i.e.*, when  $\epsilon n^* = \pi/2$ , at which point the RF spin rotator is turned off. The overall spin-evolution operator upon subsequent  $m$  idle precession turns will be

$$\begin{aligned} \mathbf{R}_{\text{evol}}(n^*, m) &= \mathbf{R}_{\text{idle}}(m) \mathbf{R}_{\text{idle}}(n^*) \mathbf{R}_{\text{env}}(n^*) \\ &= \mathbf{R}_{\text{idle}}(n) \mathbf{R}_{\text{env}}(n^*), \end{aligned} \quad (12)$$

where  $n = m + n^*$ . This representation allows an easy interpretation: the evolution of envelopes freezes at  $n = n^*$ , while the idle precession continues without interruption.

Some observations on these results are in order. The tensor polarization evolves from  $T_{yy}(0)$  to  $T_{yy}(n \geq n^*) = -T_{yy}(0)/2$ , and it does not depend on the spin-precession phase  $\theta_s n$ . The dependence of  $T_{yy}$  on the spin-rotation angle  $\epsilon n$  has been observed experimentally at COSY [46]. The dependence of  $T_{xx}$  and  $T_{zz}$  on the spin-precession angle cancels in the sum  $T_{xx}(n) + T_{zz}(n) = -T_{yy}(n)$ .

The two off-diagonal tensor polarizations  $T_{yx}(n)$  and  $T_{yz}(n)$  can be combined into the in-plane vector,  $\vec{Q}_1(n) = T_{yx}(n) \vec{e}_x + T_{yz}(n) \vec{e}_z$ , which precesses with the same idle precession frequency as the in-plane vector polarization (see also [43]). Its envelope is the product of the envelopes for  $P_y$  and  $P_{x,z}$ , and it vanishes for pure in-plane vector polarization. Similarly,  $\vec{Q}_2(n) = [T_{xx}(n) - T_{zz}(n)] \vec{e}_x + 2T_{xz}(n) \vec{e}_z$  is the in-plane vector polarization, which precesses with twice the idle precession frequency (see also [43]). Its envelope  $\sin^2 \epsilon n$  is equal to the square of the envelope of the in-plane vector polarization.

Stored vector and tensor polarized deuteron beams and internal polarized gas targets are routinely operated in high-energy spin-physics experiments. At COSY for instance, vector and tensor beam polarizations of about 0.75 and 0.6 of the ideal value, respectively, are obtained [47], while hydrogen storage cell gas targets are typically operated at nuclear polarizations of 0.75 [48]. The tensor analyzing powers in  $pd$  scattering are experimentally known to be large [49–51] and are well understood theoretically [52,53]. The robust polarimetry of diagonal tensor polarization in  $pd$  scattering is well established [46,47]. It would be very interesting to experimentally test the consistency of the phase of the spin oscillations using the tensor polarization with the one from the vector polarization. Besides that, the experimental observation of the oscillating PC tensor asymmetry in the interaction with an unpolarized proton target will directly gauge the sensitivity to the TVPC asymmetry.

#### 4. The TVPC asymmetry: signal and backgrounds

The above analysis suggests that the TVPC asymmetry,

$$A_{\text{TVPC}}(n) = -\frac{3}{4} \cdot \frac{\sigma_{\text{TVPC}}}{\sigma_0} T_{yy}(0) P_y^p \cdot \sin^2 \epsilon n^* \cdot \sin 2\theta_3 n, \quad (13)$$

constitutes a unique  $P_y^p$ -odd asymmetry, which oscillates with twice the idle precession frequency. It is readily distinguishable from the T-conserving and  $P_y^p$ -independent component of the tensor asymmetry arising from  $\sigma_{\text{T}} T_{zz}(n)$ , proportional to  $\sin^2 \epsilon n^* \cos 2\theta_3 n$ .

In the conventional approach with static polarizations, the residual  $P_{y,\text{res}}^d$  in the  $T_{xz}$  tensor-polarized deuterium target, contributes a hard to quantify  $P_y^p$ -odd background  $\propto \sigma_{\text{T}} P_{y,\text{res}}^d P_y^p$  [5,7,8]. In the novel approach described here, a possible small departure of  $\epsilon n^*$  from  $\pi/2$  shall give rise to a constant  $P_y^p$ -odd offset  $\propto \sigma_{\text{T}} P_y^p P_y^d(0) \cos \epsilon n^*$ , which does not affect the determination of the oscillating TVPC term by a Fourier analysis.

A misalignment of the proton polarization in the target with respect to the normal to the ring plane  $\vec{e}_y$  generates unwanted  $P_x^p$  and  $P_z^p$  components [see also [9]]. These will produce a background  $\vec{P}^p$ -odd signal proportional to  $P_y^d(0) \sin \epsilon n^* (\sigma_{\text{T}} P_x^p \cos \theta_3 n - \sigma_{\text{LL}} P_z^p \sin \theta_3 n)$ , distinguishable from the TVPC signal by Fourier analysis. A further unwanted contribution from misalignment is the  $P_x^p$ -odd term  $\sigma_{\text{TVPC}} T_{yz}(n) P_x^p \propto \sin \epsilon n^* \cdot \cos \epsilon n^* \cdot \sin \theta_3 n$  [see Eq. (2)]. It is part of the TVPC signal that oscillates with the idle precession frequency  $f_s$ . Besides that, this signal is suppressed because  $\cos \epsilon n^*$  is small.

Yet another oscillating background from misalignment, proportional to  $P_z^p \cos 2\theta_3 n \cdot \sin^2 \epsilon n^*$ , stems from the P-odd tensor cross section  $\sigma_{\text{PV}}^{\text{T}} P_z^p T_{zz}(n)$ . Besides  $P_z^p$  being small, this contribution is additionally suppressed by parity violation (see Sec. 6).

#### 5. Determination of the TVPV asymmetry

There are two possibilities to search for the TVPV interaction. The first approach to isolate  $\sigma_{\text{TVPV}}(\mathbf{k} \cdot [\mathbf{P}^d \times \mathbf{P}^p])$  demands for the radial polarization of target protons. The technique of switching the target polarization in sign and direction by reversing a weak guide field is described in [9]. In this case

$$\sigma_{\text{TVPV}} \mathbf{k} \cdot [\mathbf{P}^d \times \mathbf{P}^p] \propto P_y^d(0) P_x^p \cos \epsilon n, \quad (14)$$

the corresponding T-odd signal will be  $P_x^p$ -odd and has a characteristic envelope  $\cos \epsilon n$ . It is easily distinguishable from the oscillating  $\sigma_{\text{T}} P_x^d(n) P_x^p \propto \sin \epsilon n^* \cdot \cos \theta_3 n$ .

The second approach to the TVPV asymmetry is to retain the vertical polarization of protons and to take advantage of the precessing vector polarization of deuterons. In that case,

$$\mathbf{k} \cdot [\mathbf{P}^d \times \mathbf{P}^p] = P_x^d(n) P_y^p \propto P_y^p \sin \epsilon n^* \cdot \cos \theta_3 n \quad (15)$$

is  $P_y^p$ -odd, and oscillates with the frequency  $f_s$ . Furthermore, choosing a second working point,  $\epsilon n^* = 3\pi/2$ , offers an extra cross check of the T-violation property, as it amounts to the reversal of the sign of the deuteron in-plane vector polarization compared to the case of  $n^* = \pi/2$ . Thus, the oscillating signal [see Eq. (15)] can readily be isolated from the offset  $\sigma_{\text{T}} P_y^d(n^*) P_y^p$ .

The case of the TVPV asymmetry summarizes the remarkable power of the precessing-polarization approach to T-violation in  $pd$  interactions. In the same experimental setup, one can *simultaneously* search for TVPC and TVPV asymmetries with about the same sensitivity.

Next we comment on longitudinal spin asymmetries. In the case of an unpolarized target, the P-violating asymmetry  $A_{\text{PV}}^d(n) \propto$

$\sin \theta_3 n$  oscillates with the frequency  $f_s$ , and the method is equally applicable to orbiting horizontally polarized protons [13]. Apart from  $A_{\text{PV}}^d(n)$ , there will be an extra signal from the tensor polarization  $T_{zz}(n)$ , which has a component oscillating with the frequency  $2f_s$ . The two signals are readily separated by the Fourier analysis. This possibility to measure the tensor asymmetry  $A_{\text{T}} = \sigma_{\text{T}}/\sigma_0$  in the scattering of deuterons on various unpolarized internal targets comes as an extra bonus from the in-plane precessing deuteron polarization.

#### 6. New access to longitudinal spin observables: the longitudinally polarized target

To measure the P-conserving double longitudinal asymmetry  $A_{\text{LL}}$  with stored deuterons, one needs longitudinally polarized protons in the target cell [9]. For the deuteron spins in the ring plane, the observed asymmetry equals

$$A_{\text{LL}}^{\text{dp,pp}}(n) = \frac{\sigma_{\text{LL}}}{\sigma_0} P_z^d(n) P_z^p \propto P_z^p \sin \theta_3 n. \quad (16)$$

It is  $P_z^p$ -odd and oscillates with the frequency  $f_s$ . The same technique applies to stored polarized protons.

Alongside  $A_{\text{LL}}(n)$ , one will gain access to the PV tensor asymmetry  $A_{\text{PV}}^{\text{T}}$ . The signal of this asymmetry will be  $P_z^p$ -odd and will oscillate as  $\cos 2\theta_3 n$ . A conservative expectation for this asymmetry,  $A_{\text{PV}}^{\text{T}} \approx A_{\text{PV}}^p A_{\text{T}} \sim 10^{-7} \times A_{\text{T}}$ , suggests that it is hardly accessible for current experiments. To the best of our knowledge, this asymmetry has never been searched for experimentally, and the issue of  $A_{\text{PV}}^{\text{T}}$  is an entirely open one.

The approach to employ the oscillating longitudinal polarization to study the T-conserving P-violating single-spin asymmetry has already been discussed in [13]. Deep inelastic scattering of longitudinally polarized electrons off longitudinally polarized deuterons constitutes an imperative part of the spin physics program at eRHIC. Here one faces the known problems of ensuring the stable longitudinal polarization of deuterons at the interaction point [54], and it is worth to take a fresh look at the possibility of working with oscillating in-plane polarization of ultra-relativistic deuterons. In order to make this approach viable, a solution has to be found to increase the in-plane spin-coherence time of  $\sim 1400$  s, achieved so far at COSY [36,37,55], by more than one order of magnitude to match the expected storage time of  $\sim 10$  h at eRHIC [56].

#### 7. Summary and conclusions

At the moment, the T-invariance in proton-proton scattering has been tested to a moderate accuracy of  $\sim 10^{-2}$ . The new approach described here allows one to measure spin asymmetries in storage ring experiments based on the oscillating vector and tensor asymmetries of stored protons and deuterons. Such investigations to search for T-violation in  $pd$  interactions in double-polarized storage ring experiments can be performed, e.g., at COSY or NICA. The JEDI experience with precessing stored vector-polarized deuterons can readily be extended to precessing tensor-polarized deuterons.

Of special interest here is the search for millistrong CP violation in hadronic interactions as a potential source of CP violation beyond the Standard Model. Here one needs to isolate the oscillating TVPC component in the  $pd$  total cross section. One of merits of this approach is that attenuation of beams of different polarizations will be compared within the same cycle, diminishing the possible cycle-to-cycle systematics. The required tensor polarimetry is well advanced and monitoring the precessing tensor polarization is not an issue. In the case of the total cross section one needs a non-destructive measurement of the beam attenuation in the internal



polarized hydrogen gas target by comparison of the total charge of the bunch in front of and behind the target. A test experiment with beam bunches simulated by a pulsed current flowing through a wire, making use of a high-precision beam-current transformer has been conducted at IKP of Forschungszentrum Jülich. The conclusion of this study is that a measurement of the TVPC asymmetry up to an accuracy of  $10^{-6}$  is within reach [57]. We emphasize that the sensitivity to the oscillating TVPC signal can be evaluated directly by experimental observation of the oscillating tensor asymmetry using an unpolarized target.

The Fourier analysis of oscillating spin asymmetries, in conjunction with the reversal of the proton target polarization, will enable one to uniquely determine the T-violating and P-conserving asymmetry  $A_{TVPC}$ , and simultaneously the T-violating and P-violating asymmetry  $A_{TPV}$ . As a byproduct, the same technique of precessing vector polarization can be used to study concurrently in the same experimental setup a whole family of P-odd and P-even spin asymmetries.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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