Tests of fundamental discrete symmetries at NICA facility

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Abstract

A status report on studies in the framework of the Russian Fund for Basic Research Grant No. 18-02-40092 MEGA is presented. The main purpose of the project is to explore the possibilities of tests of the fundamental discrete symmetries taking advantage of high intensity beams of polarized protons and deuterons available at NICA. A focus of the report is on single-spin parity violation experiments on a test of the Standard Model based on new technique of precessing horizontal polarizations. We comment also on possible extensions of this technique to the search for semistrong CP violation beyond the Standard Model in double-polarized proton-deuteron scattering.

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INTRODUCTION

SPD project at NICA aims at polarization experiments in the collider mode. In the broader context, the main virtue of NICA facility is high current beams of polarized protons and deuterons [1, 2]. For decades to come, NICA will offer a unique access also to fixed target experimental tests of fundamental symmetries within or beyond the Standard Model (SM) and one should not overlook this opportunity.

Our knowledge about high energy parity violation (PV) in the pure non-leptonic sector of SM is as yet scarce. The most accurate result on PV asymmetry in pp scattering at 45 MeV, $A_{PV} = -(1.5 \pm 0.22)\cdot 10^{-7}$, is based on the data collected for several years [3]. A result of PV experiment at ZGS wtih 5.1 GeV protons interacting with the water target, $A_{PV} = -(26.5 \pm 6.0 \pm 3.6)\cdot 10^{-7}$, was also collected for several years [4]. Theorists failed to acomodate this anomalously large asymmetry in the SM (see review [5]). Only modest upper bounds were set at Fermilab in pp and $p\bar{p}$ interactions at 200 GeV: $A_{PV} < 10^{-5}$ [6].

We explore a feasibility of precision measurements of PV asymmetry at the NICA facility [7–9]. Our key suggestion is using beams with polarization idly rotating in the ring plane. Such a polarization has been successfully applied in 1986 at the Budker INP, with participation of members of the present team, to a precision comparison of magnetic anomalies of e^+ and e^- [10]. We also mention the 2002 idea to accelerate oscillating polarization beams in Nuclotron [11]. Subsequently, the JEDI collaboration, including members of the present team, had extended this approach to studies of fine aspects of spin dynamics of polarized deuterons stored at the COSY accelerator [12, 13]. The principal point is that time-stamped precessing polarization is as useful as the static ones: oscillating asymmetries from the in-plane precessing polarization can readily be isolated by Fourier analysis.

In this report we share our ideas on the preferred external fixed target PV experiments at the new Booster or Nuclotron. The already published collaboration results [7–9] are mentioned only briefly. Polarized deuterons are favored because the NICA energy range is free of spin resonances. An outstanding record of experimentation with polarized deuterons at the Nuclotron is noteworthy [14, 15]. The project outgrew its original boundary: it was understood that besides PV, the precessing polarization deuterons can give an access to tests of still another fundamental symmetry — the time reversal invariance [16]. Specifically, one can search for the semistrong T- and CP-violating, P-conserving and flavor-conserving interaction, suggested by Okun [17], Prentki & Veltman [18], and Lee & Wolfenstein [19]. An intriguing open issue is whether this manifestly beyond SM semistrong CP-violation can resolve the puzzle of the anomalously large baryon asymmetry of the Universe, where SM fails by nine orders in magnitude [20]. On top of that, we mention also a possibility of generating oscillating deuteron polarization at electron-ion collider eIC [16].

I. PRECESSING SPIN ASYMMETRIES IN THE TOTAL *pd* CROSS SECTION

We illustrate the polarization effect on the example of total *pd* cross section:

$$\begin{aligned}\sigma_{\rm tot} = & \sigma_0 + \sigma_{\rm TT}\left[\left(\mathbf{P}^{\rm d}\cdot\mathbf{P}^{\rm p}\right) - \left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right)\right] + \sigma_{\rm LL}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma_{\rm T} Q_{mn}k_m k_n \\ & + \sigma^{\rm p}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma^{\rm d}_{\rm PV}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right) + \sigma^{\rm T}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) Q_{mn}k_m k_n \\ & + \sigma_{\rm TVPV}\left(\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]\right) + \sigma_{\rm TVPC} k_m Q_{mn}\epsilon_{nlr} P^{\rm p}_l k_r\,.\end{aligned} \tag{1}$$

Here $\mathbf{P}^{\rm d}$ and $\mathbf{P}^{\rm p}$ are polarizations of the deuteron and proton, Q_{mn} is the tensor polarization of the deuteron, and $\mathbf{k}$ is the collision axis (the z-axis). The y-axis is normal to the ring plane, x-axis is the radial one. In the tensor polarization dependent terms $Q_{mn}k_m k_n = Q_{zz}$, and $k_m Q_{mn}\epsilon_{nlr} P^{\rm p}_l k_r = Q_{xz}P^{\rm p}_y - Q_{yz}P^{\rm p}_x$ is odd under flip of the proton polarization. The cross sections σ_0, $\sigma_{\rm TT}$, $\sigma_{\rm LL}$, and $\sigma_{\rm T}$ correspond to ordinary P-even and T-even interactions, $\sigma^{\rm p}_{\rm PV}$, $\sigma^{\rm d}_{\rm PV}$, and $\sigma^{\rm T}_{\rm PV}$ give PV signals , and $\sigma_{\rm TVPV}$ is the TVPV component, while $\sigma_{\rm TVPC}$ is the null observable for the TVPC semistrong interaction.

The equilibrium vertical spin of the stored beam is subjected to parametric resonance driven by the radiofrequency (RF) flipper (solenoid):

$$\vec{P}(n) = P_y(0)[\cos(\epsilon n)\vec{e}_y + \sin(\epsilon n)[\cos(\theta_s n)\vec{e}_x - \sin(\theta_s n)\vec{e}_z]\,. \tag{2}$$

Here n is the turn number, $\theta_s = 2\pi\nu_s$, where $\nu_s = G\gamma$ is the spin tune, G is magnetic anomaly of the particle, γ is its γ-factor, $\epsilon = 2\pi\nu_R$ and ν_R is the spin resonance tune. In this equation, $\cos(\epsilon n)$ and $\sin(\epsilon n)$ have conspicuous interpretation as envelopes of the vertical and in-plane idly precessing polarizations, respectively. The flipper is turned off when $\epsilon n = \pi/2$ is reached and then spin will keep idly precessing in the storage ring plane.

Oscillating $P_z = -P_y(0)\sin(\theta_s n)$ gives rise to the oscillating PV signal in total cross section, see Eq. 1. The internal target polarimetry of oscillating P_x is used by JEDI collaboration to monitor the spin precession frequency [12, 13] and provide the time stamp for P_z .

In our proposal this time stamp will be used to trigger the single-turn dump of beam of the desired P_z onto the external target. In JEDI experiments [21, 22] the spin coherence time of idly precessing deuterons has been maximized up to 1400 s by fine tuning the sextupole lenses, as was suggested already in 1987 by the present collaborations members (Koop and Shatunov [23]).

We mention briefly only major points about flipper driven evolution of the tensor polarization of deuterons starting with $Q_{yx}(0) = Q_{yz}(0) = Q_{xz}(0) = 0$, and $Q_{xx}(0) = Q_{zz}(0) = -\frac{1}{2}Q_{yy}(0)$ [16]:

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

At the working point $\epsilon n = \pi/2$ we have $Q_{yx} = Q_{yz} = 0$, $Q_{yy} = const$ and $Q_{xx,zz} \propto 1 \pm 3\cos 2\theta_s n$. The effect of tensor polarizations is easily separated from the PV signal by Fourier analysis.

Off-diagonal Q_{xz} enters the TVPC asymmetry which probes the semistrong CP-violating interaction. The TVPC asymmetry $\propto Q_{xz}$ has the unique Fourier signature, is P^p_y-odd, and is free of systematic background [16].

II. PV ASYMMETRY: EXPECTATIONS FROM STANDARD MODEL

The theoretical results of the team were reported in three publications [8, 9, 16]. The salient feature of the tree-level PV weak Hamiltonian is a strong suppression of the PV pp amplitude, because numerically $|4\sin^2\theta_W - 1| \ll 1$. However, the effective PV neutral current can be generated from charged current np interaction by radiative corrections from charge exchange strong interaction with encouraging magnitude, although the uncertainties are inevitably substantial [8]. The initial and final state strong interactions, aka absorption corrections, endow the initially real valued tree-level PV amplitude with the imaginary part, which can be evaluated in the eikonal approximation. The PV contribution to the total cross section is nearly exhausted by PV in elastic scattering, what entails a strong suppression of PV in inelastic scattering. The corollary is that in comparison to the total cross section, the PV asymmetry in elastic scattering will be enhanced by large factor of $\sigma_{tot}/\delta\sigma_{el} \sim 3$. The expectations from the SM for PV in proton-nucleon interactions at NICA are [8]: $\mathcal{A}^{pn}_{tot} \sim 10^{-7}$, $\mathcal{A}^{pp}_{tot} \sim 0.4 \cdot 10^{-7}$.

New features of *pd* interactions are Glauber screening and quasielastic scattering, aka diffractive breakup of the deuteron [24, 25]. The technicalities of calculations of P-odd asymmetries may be found in the publication [9]. The enhancement of the P-odd asymmetry in elastic *pN* scattering vs. total cross section will persist in both elastic and quasi-elastic *pd* scattering. A substantial difference between the scattering of polarized deuterons on unpolarized protons and the scattering of polarized protons on unpolarized deuterons has its origin in the interference of the P-odd *pp* and *pn* amplitudes.

Remarkably, to the same accuracy as in the case of *pp* scattering, the P-odd component of the total *pd* cross section is exhausted by the sum of P-odd components of the total elastic and quasielastic cross sections. Now the strong suppression of the parity violation holds for truly inelastic *pd* collisions with production of new particles (mesons).

We first report expectations for PV cross sections and asymmetries $\mathcal{A} = \sigma_W/\sigma_s$ in the scattering of polarized deuterons with $\lambda_d = 1$ on unpolarized protons:

$$\begin{aligned} &\sigma^{pd}_{s,\,tot} = 96 \ \text{mb}, \quad \sigma^{pd}_{W,\,tot} = 2.1\,\text{nb}, \quad \mathcal{A}^{pd}_{tot} = 2 * 10^{-8}\,, \\ &\sigma^{pd}_{s,\,el} = 20 \ \text{mb}, \quad \sigma^{pd}_{W,\,el} = 0.7\,\text{nb}\,, \quad \mathcal{A}^{pd}_{el} = 3.5 * 10^{-8}\,, \\ &\sigma^{pd}_{s,\,qel} = 22.4 \ \text{mb}, \quad \sigma^{pd}_{W,\,qel} = 1.4\,\text{nb}\,, \quad \mathcal{A}^{pd}_{qel} = 6 * 10^{-8}\,. \end{aligned} \tag{4}$$

For the interaction of a polarized protons with $\lambda_p = 1$ with unpolarized deuterons, we have

$$\begin{aligned} &\sigma^{pd}_{W,\,tot} = -0.8\,\text{nb}\,, \quad \mathcal{A}^{pd}_{tot} = -0.9 * 10^{-8}\,, \\ &\sigma^{pd}_{W,\,el} = -0.6\,\text{nb}\,, \quad \mathcal{A}^{pd}_{el} = -3 * 10^{-8}\,, \\ &\sigma^{pd}_{W,\,qel} = -0.2\,\text{nb}\,, \quad \mathcal{A}^{pd}_{qel} = -10^{-8}\,. \end{aligned} \tag{5}$$

III. THE EXPERIMENTAL STRATEGIES

Generic considerations of the external target option. The analysis of the optimal strategy for the PV experiment is in the formative stage. To illustrate the challenges one faces, we focus here on the option of extracted polarized deuteron beams interacting with the external target, similar to that used in the ZGS experiment with accelerated protons [4]. A source of polarized deuterons with unique parameters [14] has been commissioned at the Joint Institute for Nuclear Research decades ago, and successful sessions of their acceleration in the Nuclotron [15] have been carried out. According to [2], the Nuclotron is able to accelerate in one cycle up to $1.6{\cdot}10^{11}$ polarized protons and deuterons.

The principal target is a reach to PV asymmetries at the level $\sim 10^{-7}$ or better. On generic grounds that requires about 10^{15} events. The physics observable will be a difference of attenuations of the positive and negative helicity beams in thick dense target. To maximize the statistics, one needs large number of cycles. The typical cycle will consist of (1) injection of vertically polarized particles, (2) acceleration to the required energy, (3) rotation of polarization from the vertical to horizontal one by RF flipper, (4) the polarimetry of the in-plane precessing spin and the determination of the spin-tune and the spin phase, (5) single-turn extraction of the beam of desired helicity onto the target, (6) comparison of beam currents upstream and downstream of the target.

We skip a discussion of the routine stages (1) and (2).

The spin coherence time. The stages (3) and (4) require more attention. The vertical polarization is preserved by the vertical guiding field in the ring. The in-plane idly precessing spins decohere with time. Therefore, the stages (3) and (4) together must be shorter than the spin coherence time. Ever since the experiment [10], the RF flippers are being routinely used in the spin experiments. More detailed discussion of the proposed fast flipper will be presented below, for the purposes of the present discussion it suffices to know that the vertical spin can be rotated to the horizontal one faster than in 1 s. As the reference point we cite the JEDI result, that with beams of 10^9 deuterons of momentum 0.97 GeV/c in COSY, the spin precession phase can be measured to the accuracy of ~ 0.2 in 2 s [13, 26]. Steady operation with spin coherence time exceeding 1000 s has been achieved [21, 22]. The educated guess is that, at the same energy of deuterons, the spin coherence time will be sufficient for less that 3 s of idle precession in Nuclotron or the new Booster rings even without cooling the beam and a single cycle can be as short as ~ 5 sec. The radial polarization cycles bring the effective cycle length to ~ 10 s. Making allowance for the contingency factor of 2, we end up with ~ 130000 effective cycles per month. By the rule of thumb, in one month data taking with thick target of one absorption length, the total number of interactions can reach

$\sim 10^{16}$. A parasitic data taking, when Nuclotron and/or Booster are idling during operation of NICA in the collider mode, makes possible a further gain in the statistics.

Polarization of the ejected beam. One needs the single-turn extraction of the stored bunch. At the discussed energy, the spin tune of deuterons $\nu_s = G\gamma = -0.160977$. After 50 particle revolutions in the ring, the spin will make 8.048 in-plane rotations, after 99 revolutions the spin will make 15.966 rotations, and 23.986 in-pane rotations after 149 revolutions etc. This shows that with time stamp it will take not much longer than few hundred turns of the beam, *i.e.,*, few decimal fractions of a millisecond, to decide when to extract the beam polarized in any desired orientation. A good option is a sequence of two cycles with alternating P_z to measure the PV asymmetry, and two more cycles to crosscheck the equality of attenuations of beams with alternating radial P_x.

Polarimetry issues. Internal cylindrical scintillation polarimeter made of four, top–bottom and right–left sectors, will provide time resolution to dynamically measure the oscillating transverse polarization of the beam from the oscillating up-down asymmetry [12, 13]. The periphery of the beam can be brought to collisions with the carbon target either by stochastic heating of the beam or generating the bump by beam steerers. The polarimetry will consume only a small fraction of the beam before it is ejected into the target channel. A cycle-to-cycle stability of orbits will be controlled by beam position monitors along the ring circumference, the magnetic field will be controlled by NMR sensors in a special dipole magnet powered serially with the ring dipoles. Specific to the approach is a high precision cycle-to-cycle comparison of spin tunes, which amounts to a comparison of energies. The supplementary polarimetry of the beam after the target will provide important cross check of orientation of polarization vector of the beam incident on the target.

Flipper implementation issues. For deuterons with momentum $p = 0.97\,\mathrm{GeV}/c$ (kinematic parameters $\gamma = 1.125$, $\beta = 0.46$), it is rational to apply the longitudinal magnetic field oscillating at a relatively low frequency $f = f_c \cdot \gamma|G| = 88.3\,\mathrm{kHz}$. The ceramic vacuum chamber must have conductive longitudinal stripes on the inner surface so that the beam image currents can freely propagate along these metalized tracks. The outer side of the ceramic chamber will serve as a skeleton for winding the solenoid turns. The approximate technical parameters of the flipper [7] are shown in Table I. The necessary power to the RF generator, 5 kW, can be provided, for instance, by the generator triode GI-50, capable of delivering up to 40 kW of power in a continuous mode, with the help of modern semiconductor amplifiers. We leave this question for future study.

Table I. The main flipper parameters for the deuteron momentum 0.97 GeV/c and the amplitude of its circular harmonic $w = 2.5 \cdot 10^{-5}$ (field integral $Bl = 1.2 \cdot 10^{-3}$ T· m)

Solenoid length	1.0	m
Magnetic field amplitude	0.0012	T
Spiral winding diameter	150	mm
Aperture of the ceramic vacuum chamber	120	mm
Case diameter	400	mm
Solenoid turns	80	
Winding inductance	150	μH
Characteristic impedance of the circuit	75	Ohm
Active loss resistance	0.2	Ohm
Quality factor of the oscillating circuit	375	
Winding current	150	A
Inductive voltage	11	kV
Active loss power	4.5	kW

The accuracy issues in the external target mode. With N_1 particles impinging on the target and N_2 particles left behind the target, the total beam loss cross section $\sigma_{\rm tot}$ per target nucleus is derived from the exponential attenuation law, $N_2 = N_1 \cdot \exp(-\sigma_{\rm tot}\rho)$, where ρ is target density: $\sigma_{\rm tot} = \rho^{-1}\ln(N_1/N_2)$, $\delta\sigma_{\rm tot} = \rho^{-1}(\delta N_1/N_1 - \delta N_2/N_2)$. We estimate the dispersion of the measured number of particles N following the $\sqrt{N}$ law, so that $\langle \delta N_1^2 \rangle = N_1$. For the transmitted beam, allowance for the dispersion of the transmission coefficient p gives the corrected formula $\langle \delta N_2^2 \rangle = N_2 + p(1-p)N_1$. The best rms accuracy of measuring loss cross-section is achieved at $p = e^{-2}$:

$$\frac{\delta(\sigma_{\rm tot})}{\sigma_{\rm tot}} = \sqrt{\frac{2}{p\ln^2 p}} \cdot \frac{1}{\sqrt{N_1}} \Rightarrow \frac{e}{\sqrt{2}} \cdot \frac{1}{\sqrt{N_1}} = \frac{1.92}{\sqrt{N_1}} \,. \tag{6}$$

Above we argued that $\sim 1.6 \cdot 10^5$ cycles per month are feasible. Consequently, in order to achieve the statistical accuracy of 10^{-7} in measuring the loss cross-section in the one-month run, it is necessary to ensure the accuracy of the asymmetry measurement in the single cycle at the level of $A_1 \approx 4 \cdot 10^{-5}$. The number of particles in the bunch impinging on the target must be no less than $\approx 2.3 \cdot 10^9$. This leaves a certain room for the further improvement of sensitivity to PV asymmetry increasing the number of particles in the bunch. Furthermore, in the parasitic mode the data taking can be stretched beyond one month.

One can view two options to measure the number of particles in the beam. The first one is to resort to ionization chambers or secondary emission sensors with multiplication of secondary particles. With n secondary particles produced per one primary particle in the final state, total number of secondary particles will be $N \cdot n$, what entails the relative rms fluctuation in determination of the number of particles in the beam

$$\frac{\delta N}{N} = \frac{\delta(Nn)}{Nn} = \sqrt{\frac{1}{Nn}}.$$

An alternative option is a non-destructive measurement of the total charge of the bunch before and after interaction in the target - a comparison of charges before and after amounts to desired comparison of particle numbers $N_{1,2}$. Such an approach will take advantage of bunched beam required for the time stamp of the precessing polarization. Namely, the Rogowski coils with high permeability amorphous iron core are known to be good transformers of the current from the primary circuit, *i.e.,* the beam current, to the secondary circuit with a very high degree of identity. This is largely due to the very large ratio of the magnetizing inductance of the core to the leakage inductance.

The primary signal from the Rogowski coil is a voltage proportional to the time derivative of the beam current: $U = L\dot{I}$. This signal is applied to the infinitely large resistance of the amplifier buffer stage. Next, it is subjected to analog integrations on operational amplifiers (OA), composed of an RC chain. The first integration will give at the output a signal $U_1(t) = L \cdot I(t)/R_1C_1$. After the second integration, we get at the output an almost constant voltage U_2 and the accumulated charge q_2 on the capacitor C_2 will equal

$$U_2 = \frac{q \cdot L}{R_1R_2C_1C_2}, \qquad q_2 = \frac{q \cdot L}{R_1R_2C_1}.$$

With a large ratio $L/(R_1R_2C_1)$, one can get a significant gain in the accumulated charge on the capacitor of the second integrator. Note that the values of the time constants of the RC chains do not in any way affect the linearity of signal conversion by the integrator on the OA, in contrast to its passive analogue, where the signal is integrated imperfectly, with damping determined by the time constant $\tau = RC$. Leaving aside the question of the magnitude of the noise in the signal processing circuit for the current coils, we can state that it is promising to use the above approach to measure the transmission coefficient of a beam through a dense target in the transport channel from the Nuclotron or the new Booster.

One can further increase the overall statistical accuracy of measuring the beam transmission coefficient installing 3–5 identical devices both in front of, and after the target. Besides better statistics, that will allow for the mutual control of the received data from all sensors. In principle, the above considerations of performance of the Rogowski coils as beam current transformers can be studied in the test stand experiment simulating the particle bunches by the current pulses.

IV. SUMMARY AND OUTLOOK

High intensity beams of polarized deuterons available at NICA facility make feasible high precision PV tests of the Standard Model. We consider the external fixed dense target experiments at either Nuclotron or new Booster most promising ones. At the core of our proposal is a new technique of polarization precessing in the ring plane, which enables one to eject onto the target beams of any desired orientation. There are still open questions, but by statistics consideration the PV asymmetries smaller than 10^{-7} are within the reach of the proposed scheme. The only two new devices, the RF spin flipper and internal target polarimeter, can be made sufficiently compact to fit into the Nuclotron and/or the new Booster ring. The Booster may be preferred for the less crowded ring lattice. A possibility of conducting the PV asymmetry experiment in the parasitic mode needs more scrutiny.

For the lack of space, we omitted a number of items, including the spin resonance issues in operation with polarized protons, possible PV experiment with the internal dense target, selection of elastic events at high energies etc. We sketched only briefly a search for the semistrong CP violation which requires the internal polarized proton ABS target. The theoretical analysis of PV in polarized deuteron-nucleus interactions is in progress.

At electron-ion colliders, one can not produce longitudinal polarization of deuterons resorting to Siberian snakes, because of the impractically large required field integrals The ideas of operation at the integer spin tune, developed at JINR [28, 29], have been further extended at BNL [27]. A fresh look at the possibility of oscillating in-plane polarization of ultra-relativistic deuterons is worthwhile. A solution has to be found to increase the horizontal spin coherence time of ~ 1400 s, achieved so far at COSY [21], by more than one order of magnitude to match the expected storage time of ~ 10 h at eIC [30].

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