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INVESTIGATION OF SPIN-DECOHERENCE IN THE NICA STORAGE RING FOR THE FUTURE EDM-MEASUREMENT EXPERIMENT

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Abstract

A new experiment to measure electric dipole moments (EDMs) of elementary particles, based on the Frequency Domain method, has been proposed for implementation at the NICA facility (JINR, Russia). EDM experiments in general, being measurement-of-polarization experiments, require long spin-coherence times at around 1,000 seconds. The FD method involves a further complication (well paid off in orders of precision) of switching the polarity of the guiding field as part of its CW-CCW injection procedure. This latter procedure necessitates a calibration process, during which the beam polarization axis $\bar{n}$ changes its orientation from the radial (used for the measurement) to the vertical (used for the calibration) direction. If this change occurs adiabatically, the beam particles' spin-vectors follow the direction of the polarization axis — which undermines the calibration technique; however, concerns were raised as to whether violation of adiabaticity could damage spin-coherence. These concerns are addressed in the present investigation.

FREQUENCY DOMAIN METHOD

The proposed frequency domain method is a modification of the original "frozen spin" concept developed at Brookhaven National Laboratory [1–3].

The "frozen spin" family of EDM experiments has its foundation in the Thomas-Bargmann-Michel-Telegdi (T-BMT) spin precession described by the equation

$$\frac{\mathrm{d}\boldsymbol{S}}{\mathrm{d}t} = \boldsymbol{d}\times\boldsymbol{E} + \boldsymbol{\mu}\times\boldsymbol{B} = \boldsymbol{S}\times(\boldsymbol{\Omega}_{EDM} + \boldsymbol{\Omega}_{MDM}),$$

where $\boldsymbol{d}$, $\boldsymbol{\mu}$ are, respectively, the particle's electric and magnetic dipole moments, $\boldsymbol{\Omega}$'s are the corresponding spin-precession frequencies, and $\boldsymbol{S}$ is the precessing spin-vector.

In general, in order to utilize the T-BMT phenomenon for EDM-measurement in a "combined" storage ring, one introduces a radial electric field E_r. Then the accelerator's guiding field rotates the beam particles' spin-vectors via the magnetic dipole moment (MDM) at a frequency Ω_{MDM} in the horizontal plane, whereas E_r in the vertical plane with a frequency $\Omega_{EDM} \ll \Omega_{MDM}$ (see Fig. 1). One observes the vertical component of the beam polarization to oscillate:

$$P_v = P\frac{\Omega_{EDM}}{\Omega}\sin(\Omega\cdot t + \theta_0),$$
$$\Omega = \sqrt{\Omega^2_{EDM} + \Omega^2_{MDM}},$$

which we will call "the EDM-signature" signal.

The "frozen spin" method takes its name after the idea of "freezing" the MDM-precession, so that the spin precession plane turns completely vertical and the EDM-signature's amplitude is maximal. In theory, this also causes $P_v \approx P\cdot\Omega_{EDM}\cdot t$, so that one observes a slow linear buildup of vertical polarization at a rate proportional to the EDM. By measuring the amount of buildup ΔP_v per set time period T one can evaluate Ω_{EDM} and from that – the EDM itself. We may call it an "amplitude" (or "space domain") method, since the observable $P_v(T)$ is a realized fraction of the originating signal's amplitude, P (respectively, the magnitude of $\Delta\boldsymbol{P}_v$).

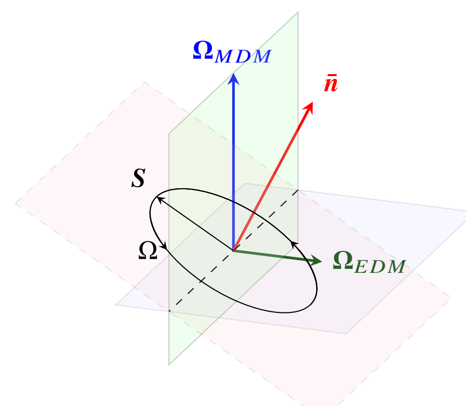

Figure 1: Thomas-BMT spin-precession. ($\boldsymbol{\Omega}_{EDM}$ has been extended by orders of magnitude for visual expediency).

However, E_r is only capable of reducing the *vertical* component of $\boldsymbol{\Omega}_{MDM}$. The radial component remains unaffected and is a major source of systematic errors. It also completely undermines any attempts at observing a *linear* polarization growth – unless Ω_r^{MDM} is made sufficiently small, which puts stringent conditions on the optical elements' installation precision.

Instead of trying to minimize the installation errors so as to purify the EDM-signature of *all* MDM contribution we could try to estimate the EDM from the signature signal's net frequency $\boldsymbol{\Omega} = \boldsymbol{\Omega}_{EDM} + \boldsymbol{\Omega}_{MDM}$. Since that frequency is a linear combination of both effects, two measurement cycles are required, in which the guiding field's polarity is reversed,

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thus changing the sign of the MDM frequency component. Then the EDM effect is estimated as

$$\hat{d} = \frac{1}{2}\left[\hat{\Omega}^{CW} + \hat{\Omega}^{CCW}\right],$$

with

$$\Omega^{CW} = \Omega_{EDM} + \Omega_r^{MDM},$$
$$\Omega^{CCW} = \Omega_{EDM} - \Omega_r^{MDM}.$$

Here CW (clockwise) and CCW (counter-) refer to the direction of beam circulation.

For a more detailed overview of three main approaches to the measurement within the "frozen spin" family please see [4].

UNADIABATIC SPIN AXIS FLIPPING

Since two frequency estimates are involved in the definition of an EDM-estimate, there arises the problem of equalizing the two measurement cycles with respect to their MDM effects' magnitudes, Ω_r^{MDM}. In order to do so, we propose to split the measurement cycle into two sub-sections: equalization and measurement proper. The spin precession axis in the two sub-sections points in orthogonal directions: vertically during equalization and horizontally for the measurement part of the cycle. In other words, the spin precession axis needs to be flipped 90° in the course of a single cycle.

The initial "equalization" section serves as a "point of continuity" for the cycles with opposite polarities. The idea here is that $\boldsymbol{\Omega} = \boldsymbol{\Omega}(\gamma)$ and there's a unique point γ_0 at which $\Omega_v(\gamma_0)$, determined predominantly by the MDM, equals zero. Since the relationship between Ω_v^{MDM} and Ω_r^{MDM} is fixed by the optical lattice, which doesn't change from cycle to cycle, what is required in order to $|\Omega_{MDM}^{CW}| = |\Omega_{MDM}^{CCW}|$ is that the $\Omega_v = 0$ in the respective cycles. Obviously, the point $\Omega_v = 0$ is indifferent to the direction the spin-vector precesses, so it is where the CW and CCW spin-precessions meet.

However, the necessity of flipping a "living" cycle's polarization axis $\bar{\boldsymbol{n}}$ raises the following concern. If the axis' rate of change $\dot{\bar{\boldsymbol{n}}}$ exceeds Ω, the spin-precession rate about that axis, then the angle $\angle(\boldsymbol{S}, \bar{\boldsymbol{n}})$ is not invariant, resulting in a variation (ultimately, the diminution) of the beam polarization $\boldsymbol{P} = \sum_j (\boldsymbol{S}_j, \bar{\boldsymbol{n}})\bar{\boldsymbol{n}}$. Hence, in order to preserve the polarization the following condition must obtain:

$$\dot{\bar{\boldsymbol{n}}} \ll \Omega. \tag{1}$$

It is important to note, though, that there is no logical necessity that the spin-vector ensemble's *internal coherence* is disrupted when violating the adiabaticity condition (1); and it is this internal coherence that is of consequence to the "frequency" approach to EDM measurement, since, in order to maximize the signature signal's amplitude, it already operates with a beam whose $\langle \boldsymbol{P} \rangle = \sum_j (\boldsymbol{S}_j, \bar{\boldsymbol{n}})\bar{\boldsymbol{n}} = \boldsymbol{0}$. We must distinguish between "depolarization" and (spin-)decoherence; it is the latter that is of concern to the proposed experiment.

SPIN-DECOHERENCE

By "spin-decoherence" we understand a systematic growing of the spin-vector ensemble's dispersion (see Fig. 2). In the standard formalism, spin-vector evolution in a storage ring may be described by the spin-transfer matrix [5]

$$T = \exp\left(-\imath\pi\nu\boldsymbol{\sigma}\cdot\bar{\boldsymbol{n}}\right),$$

where $\boldsymbol{\sigma}$ stands for the vector of Pauli matrices, and $\nu = \Omega/\omega_{cyc}$, the spin-precession frequency normalized by the cyclotron frequency, is called "spin-tune." The spin-precession axis $\bar{\boldsymbol{n}}$ is, in general, different for every particle in the beam, and depends on the particle's equilibrium energy level.

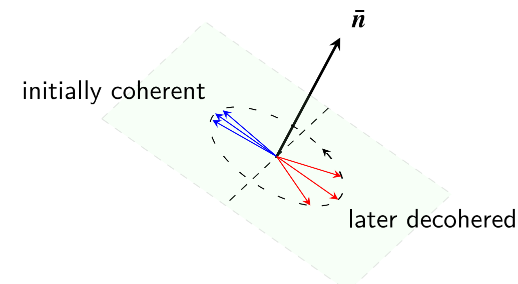

Figure 2: Spin-decoherence visualization.

Depending on experimental context, three generating mechanisms can be identified for the decoherence effect: spin-tune dispersion, $\bar{n}$-dispersion, and the angle $\angle(\boldsymbol{s}, \bar{\boldsymbol{n}})$ growth. In the experiments working with a zero-expectation-value polarized beam, the leading cause, operative in the steady state, is the first. The relevant study has been presented in [6]. In this study we took a closer look at the third cause, operative during transition phases.

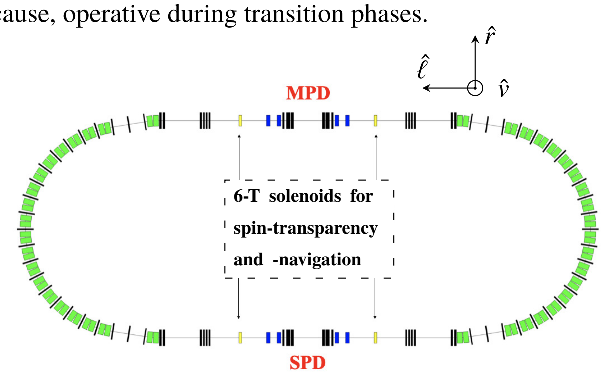

Figure 3: The optical lattice used in numerical simulation.

MODELING

In order to model the effects of adiabaticity violation on the beam's internal spin-coherence we

1. Injected a 100%-polarized beam $\left(\forall \boldsymbol{s}\ \angle(\boldsymbol{s}, \bar{\boldsymbol{n}}) = 0\right)$ into a lattice utilizing two mutually-unbalanced sets of Siberian Snakes for spin-transparency and spin-navigation (see Fig. 3 and reference [7]);
2. The navigators set a constant spin-precession frequency $\Omega = 0.86°$/turn and an angle $\psi = \angle(\hat{\ell}, \bar{\boldsymbol{n}})$ which is reset after each turn $\psi_j = \psi_{j-1} + \Delta\psi$ at the rate $\dot{\psi}$;

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3. This is tried for several different $\dot{\psi} = \Delta\psi$/turn.

All modeling was done by means of the COSY Infinity environment [8].

RESULTS AND CONCLUSIONS

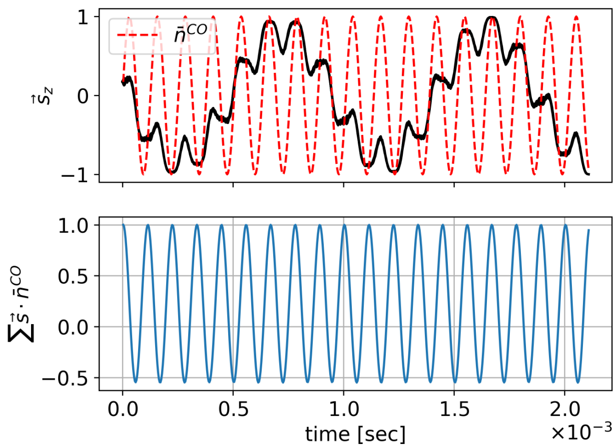

Figure 4: Depolarization in the case of a violation of the adiabaticity condition: $\dot{\bar{n}} \approx 10 \cdot \Omega$. **Top panel**: time-scan of the ensemble's spin-vectors (black solid) versus the invariant spin axis (red dashed). **Bottom panel**: polarizaton time-scan. As expected, the adiabaticity condition violation causes a heavy fluctuation of polarization, yet there is no indication of a diminution of the oscillation's amplitude; hence – no decoherence.

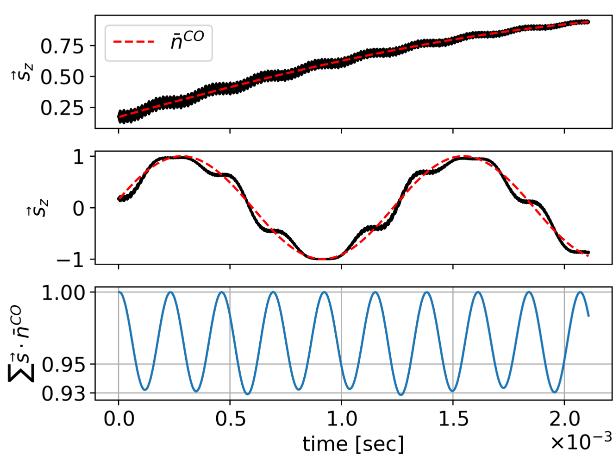

Figure 5: Time-scan of the ensemble's spin-vectors versus the invariant spin axis in the other two significant cases: $\dot{\bar{n}} \approx 0.1 \cdot \Omega$ (adiabatic case, top panel) and $\dot{\bar{n}} \approx \Omega$ (boundary case, middle panel). Also, the polarization plot for the latter (bottom panel).

The results are presented in Figs. 4 and 5. They exhibit the presence of an inertia in the spin-vectors' following of the precession axis $\bar{\boldsymbol{n}}$ when the latter's rate of change exceeds the spin precession rate Ω. The polarization plots' oscillatory pattern is due to the precession axis' (confined to the vertical plane v-ℓ) continuous rotation about the radial axis $\hat{r}$ (see Fig. 3). Neither damping in the polarization plots (bottom panels in Figs. 4 and 5), nor dispersion in the spin-vector ensembles over time (upper panels) show themselves. This means that spin coherence is not disrupted when the adiabaticity condition (1) is violated.

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