Theorist's view on the EDM at storage rings

What is the JEDI record $\mathbf{10^{-10}}$ spin tune precision good for the EDM?

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Symmetry test in Nuclei and Atoms, KITP, Santa Barbara

September 19-23, 2016

I simply extend Frank Rathman's talk:

- EDM signal = precession of spin in the E-field.
- Identical to the all to familiar MDM caused precession in the B-fieltd
- The electrically neutral neutrons can readily be stored in bottles and their spins be subjected to strong E-fields
- The charged protons & deuterons shall promptly fly away from the E-field
- Make the E-field a companion to a B-field as a confining force in a storage ring

- A challenge: *how to disentangle a tiny EDM torque on spin from the much stronger background from the MDM in imperfection magnetic fields?*
- Prime motivation for the JEDI-2014 run at COSY: Yannis Semertzidis' idea of the RF Wien filter approach to EDM at all-magnetic rings
- Imperfections fields as a show stopper?
- Ultra high precision spin tune as a unique probe of spin dynamics
- The first in situ measurement of the stable spin axis to μrad precision
- Outlook

COSY as a testing ground for the EDM searches

Часть рисунка с идентификатором отношения rId3 не найдена в файле.

- *Frenkel-Thomas-BMT eqn.* $\frac{d\vec{S}}{dt} = \left(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}\right) \times \vec{S}$

$$\vec{\Omega}_{MDM} = -\frac{q}{m}\left(G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} - \frac{G\gamma}{\gamma + 1}\vec{\beta}\left(\vec{\beta} \cdot \vec{B}\right)\right)$$

$$\vec{\Omega}_{EDM} = -\frac{q}{m}\eta\left(\vec{E} + \vec{\beta} \times \vec{B}\right)$$

η= EDM/MDM

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{\beta} \times \vec{B}\right)$$

$$\hat{R} = \exp(-i\pi\nu_s\vec{\sigma} \cdot \vec{c}) = \cos\pi\nu_s - i(\vec{\sigma} \cdot \vec{c})\sin\pi\nu_s$$

$$\vec{c} = \left(\vec{e}_x \sin\xi + \vec{e}_y \cos\xi\right)$$

$$\tan\xi = -\frac{\eta}{G}\beta$$

$$\nu_s^0 = G\gamma$$

$$\nu_s = \frac{G\gamma}{\cos\xi_{edm}}$$

EDM vs. MDM (learnt from Lev Okun in 60's)

- MDM μ_N is allowed by all symmetries
- A scale is set by a nuclear magneton

- Buy CPT
- EDM is P and CP =T forbidden

- Pay price for the parity violation: 10^{-7}
- Pay price for the CP and Time reversal violation
- $d_N = \mu_N \times 10^{-7} \times 10^{-3} \sim 10^{-24} e \cdot cm$

- The SM: CP violation linked to the flavor change. Pay 10^{-7} more to compensate for the flavor change
- $d_{N,SM} \sim \mu_N \times 10^{-7} \times 10^{-3} \times 10^{-7} \sim 10^{-31} e \cdot cm$

RF WF locked to the spin tune: EDM driven vertical spin from the horizontal one

$$S_y(t) = \frac{\psi}{2}\sin\xi_{edm}\cdot t$$

- The resonance strength is:

$$\epsilon = \frac{1}{2}\chi_{wf}|\vec{c}\times\vec{w}| = \frac{1}{2}\chi_{wf}\sin\xi_{edm}$$

- The MDM spin kick χ_{wf} in the **EDM-transparent** WF conspires with the EDM driven tilt of the stable spin aixs (Yannis Semertzides et al.)
- How to determine the stable spin axis? Add tunable Artificial Magnetic Imperfection (AI)

$$\hat{t}_a = \cos\frac{1}{2}\chi_a - i(\vec{\sigma}\cdot\vec{k})\sin\frac{1}{2}\chi_a$$

$$\cos\pi(\nu_s + \Delta\nu_s) = \frac{1}{2}Tr\hat{T}$$

$$= \cos\pi\nu_s\cos\frac{1}{2}\chi_a - (\vec{c}\cdot\vec{k})\sin\pi\nu_s\sin\frac{1}{2}\chi_a$$

- Measure stable spin axis by mapping the spin tune vs AI: dual to the RF WF approach

Magnetic imperfection as a show stopper to RF WF?

- COSY has never been meant to be a precision spin ring (a design of 80's)
- Rolls and off-sets of magnetic elements generate radial and longitudinal imperfection B-fields
- MDM in a radial imperfection B-field is a direct background to the EDM in a radial motional E-field
- The AI approach: the radial AI B-field would disturb the beam orbit --- a no go!
- Longitudinal fields do not disturb the orbit.

- In the experiment with two solenoids, the beam is prepared for spin tune measurement (a). When the solenoids were switched on, the spin tune jumps by $\Delta\nu_s$, as determined in the spin tune analysis (b):

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Poor man's solution: solenoids of two coolers at COSY at makeshift AI's

"Transport" the 2nd AI next to the 1st one

$$\hat{T} = \hat{R}_2\hat{t}_2\hat{R}_1\hat{t}_1 = \hat{R}_2\hat{R}_1\hat{R}_1^{-1}\hat{t}_2\hat{R}_1\hat{t}_1$$

$$\vec{n}_R \approx \cos\pi\nu_1\,\vec{e}_z - \sin\pi\nu_1\,\vec{e}_x$$

We furnished an effective orbit-distortion free radial B-field

$$\cos(\pi\nu_s) - \cos(\pi[\nu_s + \Delta\nu_s(\chi_1,\chi_2)]) =$$
$$= (1+\cos\pi\nu_s)\sin^2\left(\frac{1}{2}\chi_+\right) - \frac{1}{2}a_+\sin(\pi\nu_s)\sin\chi_+$$
$$-(1-\cos\pi\nu_s)\sin^2\left(\frac{1}{2}\chi_-\right) + \frac{1}{2}a_-\sin(\pi\nu_s)\sin\chi_-$$
$$\chi_\pm = \frac{1}{2}(\chi_1 \pm \chi_2)$$
$$a_\pm = (\vec{c}\cdot\vec{n}_R) \pm (\vec{c}\cdot\vec{n}_1)$$

Measurement scheme of spin tune mapping

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Measurement scheme of spin tune mapping

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Measurement scheme of spin tune mapping

- Saddle point prediction is OK, but 10σ residual discrpepancy (1 per cent of the observed spin tune jump)
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$\Delta\nu_s$

$$\nu_{res} = \Delta\nu_s^{fit} - \Delta\nu_s^{data}$$

The culprit: orbit excursions from misaligned cooler solenoids ?

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Count rate jumps from the orbit excursions

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$$\chi_1 = -0.0044\,rad, \chi_1 = -0.0297\,rad$$

Orbit excursions vs. the initial orbit setting: linear optics as expected

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Impact of the orbit excursions on the spin transfer in the ring: COSY Infinity simulations

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Measurement scheme of spin tune mapping

$$\delta_y \nu_s(\xi,\chi) = A_y \xi \chi(\chi_{arc} + \chi_0) + B_y \xi \chi^2$$

$$\cos\pi(\nu_s + \Delta\nu_s)$$
$$= \cos\pi(\nu_s + \delta\nu)\cos\frac{1}{2}\chi_a - ((\vec{c} + \delta\vec{c}) \cdot \vec{e}_z)\sin\pi(\nu_s + \delta\nu)\sin\frac{1}{2}\chi_a$$

$$\Delta_y \nu_{res} = \delta_s \nu + \frac{1}{2\pi} Y_z \xi \chi^2$$

$$c_z = \frac{1}{2}(A_+ - A_-)$$
$$c_x = -\frac{1}{2}(\tan\pi\nu_s\, A_+ + \cot\pi\nu_s\, A_-)$$

Spin tune mapping: superficial rescaling of the spin kick in AI's (don't blame power supplies!)

$$k_- - 1 = -0.0097 \pm 5 * 10^{-4}$$

$$k_+ - 1 = -0.004677 \pm 3.5 * 10^{-5}$$

$$c_+ = 0.0024703 \pm 5.1 * 10^{-7}$$

$$c_- = -0.0002263 \pm 5 * 10^{-7}$$

$$B_{+-} = -(16.6 \pm 1.7) * 10^{-5}$$

$$|d_D| < \frac{e}{m_D} \cdot \frac{G}{\beta} |\delta \vec{c}| \sim 10^{-20} e \cdot cm$$

Conclusions and Outlook

- A reinterpretation of the JEDI-2014 result: the AIs can compensate for the ring imperfection to a μrad accuracy
- Only the EDM+MDM signal is constrained
- The RF WF approach is only capable of a tentative upper bound on the EDM barring strong cancellations
- JEDI is looking forward to a more sofisticated EDM rotators to disentangle the pure EDM signal
- The spin tune mapping may find novel applications for the ring diagnostics and feedback systems to stabilize the ring

Thank you for the attention!

Measurement scheme of spin tune mapping

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Measurement scheme of spin tune mapping

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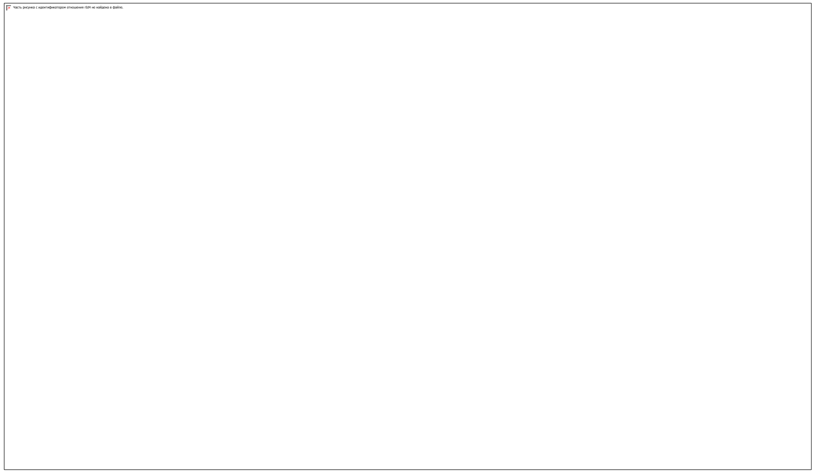
- **Compensate for the imperfection magnetic fields in a ring by fine tuning the combined AI**

$$\tan\frac{1}{2}\chi_a \left[\cos\pi\nu_s\,\vec{k} + c_y \sin\pi\nu_s\,\vec{e}_y \times \vec{k}\right] = -\sin\pi\nu_s \cos\frac{1}{2}\chi_a \vec{c}_{\parallel}$$

Measurement scheme of spin tune mapping

- When the solenoids were switched on, the spin tune was shifted by $\Delta\nu_s$, as determined in the spin tune analysis:



Summary

- The record 10^{-10} precision converts a spin tune variations into unprecedented tool for diagnostics of the spin dynamics in the ring.
- A good theoretical understanding: a saddle point prediction has been fully confirmed
- A proof of principle: the residual spin tune mismatches are orders in magnitude smaller than the spin tune shifts itself
- JEDI looks forward to successful conduction of the precursor EDM experiment with RF Wien filter

Thank you for attention!

Measurement scheme of spin tune mapping

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Measurement scheme of spin tune mapping

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