Testing Lorentz Symmetry using Deuterium

A. Nanda[1,a], S. Lahs[2], M. Simon[1], E. Widmann[1], D. Comparat[2]

[1]Stefan Meyer Institute for Subatomic Physics, ÖAW, Vienna, Austria

[a]Vienna Doctoral School in Physics, Univesity of Vienna, Vienna, Austria

[2]Univesité Paris-Saclay, Laboratoire Aimé Cotton, CNRS, Orsay, France

ÖAW AUSTRIAN ACADEMY OF SCIENCES

WWW.OEAW.AC.AT

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A new Rabi type spectrometer has been built and currently being used to study the sidereal variation signals in the hyperfine structure of Deuterium. Such signals form a crucial test for Lorentz and CPT symmtery as indicated in the Standard Model Extension.

Background: Lorentz Symmetry and SME

Observable experimental signatures of effective field theories at Planck Scale get suppressed.

The suppression factor is proportional to the ratio $\frac{m_W}{m_P} \sim 10^{-17}$ and its higher exponents.

Other approaches such as string theory realised Lorentz and CPT symmetry as low energy signal. Inspired from this, the SME was introduced to assist searches for CPT and Lorentz symmetry violation [1].

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \frac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

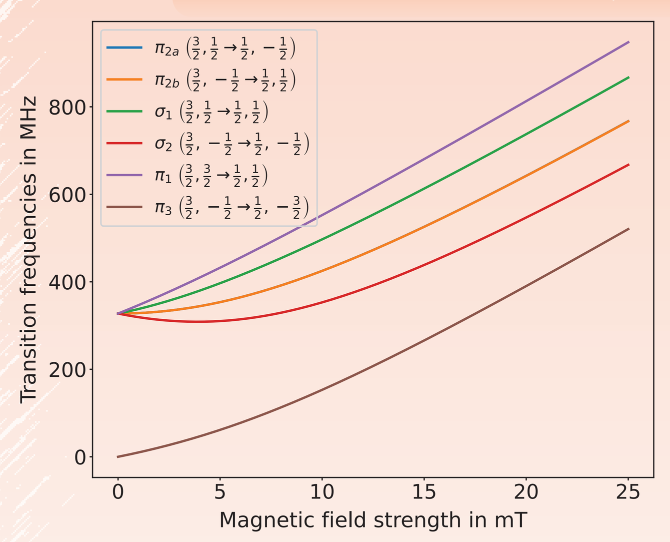
SM Dirac eqn. — CPT & Lorentz Violation — Lorentz Violation

[1] Vargas, A.J. Symmetry **2019**, 11, 1433

Models at Planck Scale

Standard Model — General Relativity

Deuterium Hyperfine Splitting



Energy level shifts in deuterium hyperfine structure based on the (F, m_F) values are predicted as follows by the SME [2]:

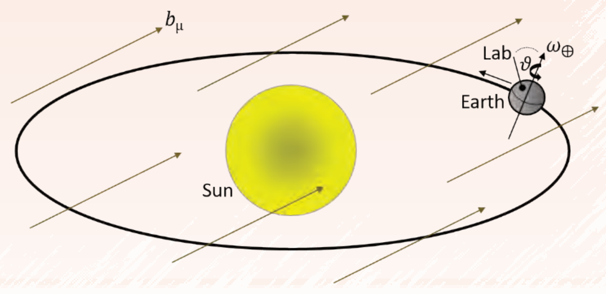
$$\delta\epsilon(F,M_F) = \frac{1}{\sqrt{5\pi}}\frac{2F-1}{(8m_F^2-10)}\sum_{q=0}^{2}\langle \mathbf{p}_{pd}^{2q}\rangle' \sum_{\mathcal{W}}\mathcal{V}^{NR}_{\mathcal{W}2q20} - \frac{1}{3\sqrt{6\pi}}\frac{m_F}{2^{F-2}}\sum_{q=0}^{2}\langle \mathbf{p}_{pd}^{2q}\rangle \times \sum_{\mathcal{W}}\left(\mathcal{T}^{NR(0B)}_{\mathcal{W}(2q)10} + \mathcal{T}^{NR(1B)}_{\mathcal{W}(2q)10}\right) - \frac{m_F}{3\sqrt{3\pi}}\sum_{q=0}^{2}\frac{(\alpha m_r)^{2q}}{(2F-1)}(1+4\delta_q^2)\times\left(\mathcal{T}^{NR(0B)}_{e(2q)10} + \mathcal{T}^{NR(1B)}_{e(2q)10}\right)$$

Relative momentum of proton in deuterium core is ~ 100 MeV. ➡ $\langle \mathbf{p}_{pd}\rangle$

This leads to 9- or even upto 18-orders of magnitude enhanced sensitivity for deuterium HFS to SME as compared to hydrogen.

Deuterium HFS: Nuclear Spin + Electron Spin, F = 3/2 quadruplet and F = 1/2 doublet.

1 Sidereal Day = 23 hours 56 minutes 4.0905 seconds. Possible SME signals at sidereal frequency or its higher harmoincs[2,3].



[2] VKostelecký, V. A., Vargas, A.J. Phys. Rev. D **92**, 056002 (2015)

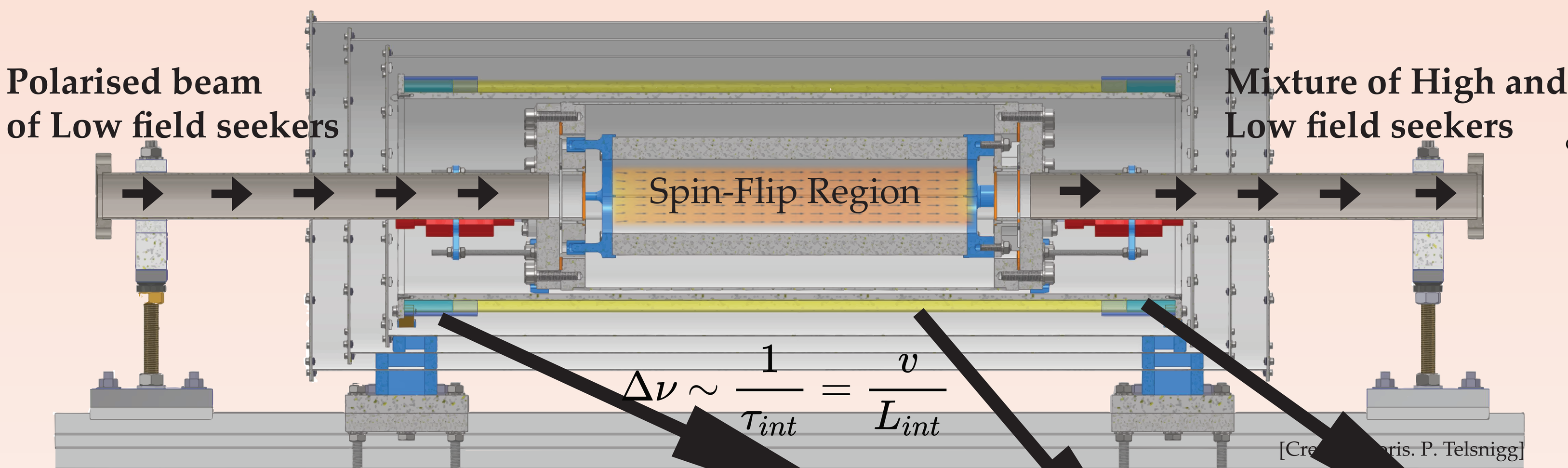
[3] Lehnert, R. Hyperfine Interact **193**, 275 (2009)

Methods and Apparatus: Rabi type Spectroscopy

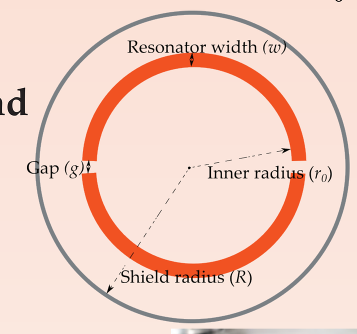
$$\omega_0 = \frac{c}{r_0}\sqrt{\left(1+\frac{A_1}{A_2}\right)\left(\frac{n\cdot g}{\pi w}\right)\left(\frac{1+\Delta Z/Z}{1+\Delta w/w}\right)}$$

$$A_1 = \pi r_0^2 \qquad A_2 = \pi\left[R^2 - (r_0+w)^2\right] \quad [4]$$

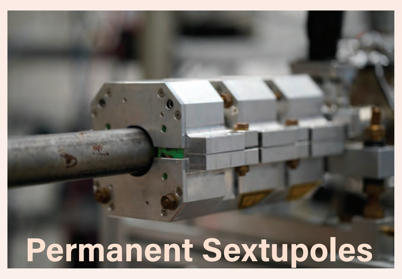
[4] M. Mehdizadeh, et. al., IEEE Transactions on Microwave Theory and Techniques, 31(12), Dec 1983

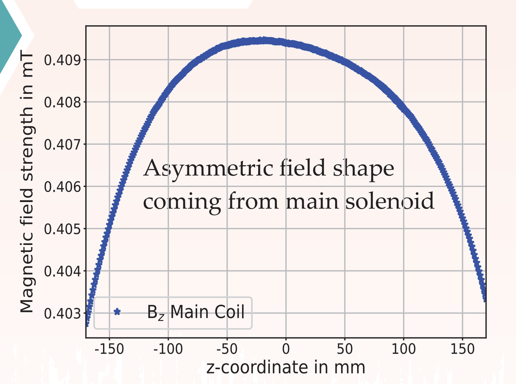


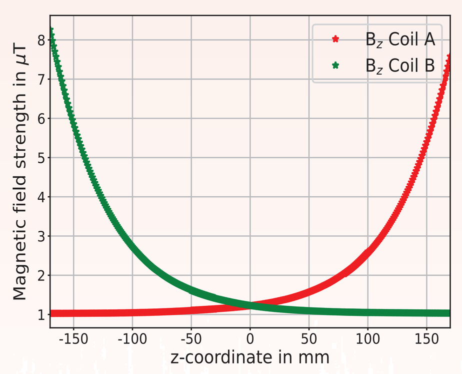
$$\Delta\nu \sim \frac{1}{\tau_{int}} = \frac{v}{L_{int}}$$

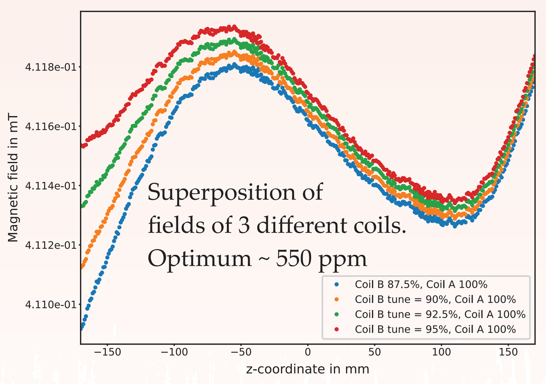


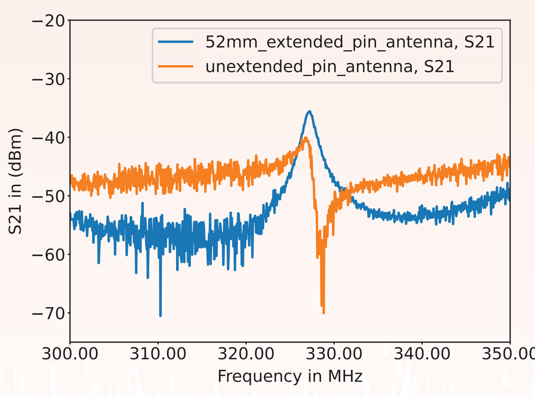
Double Split Ring Resonator

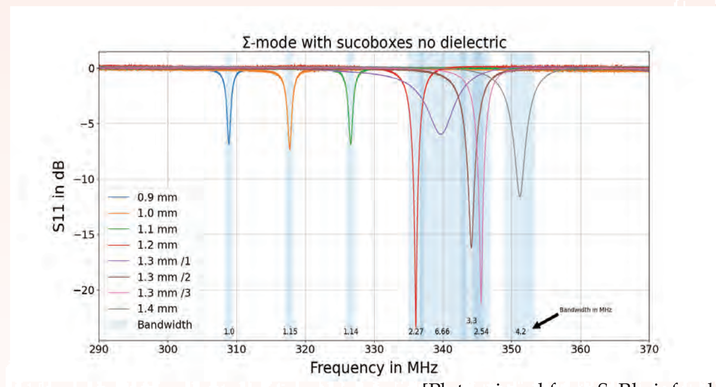










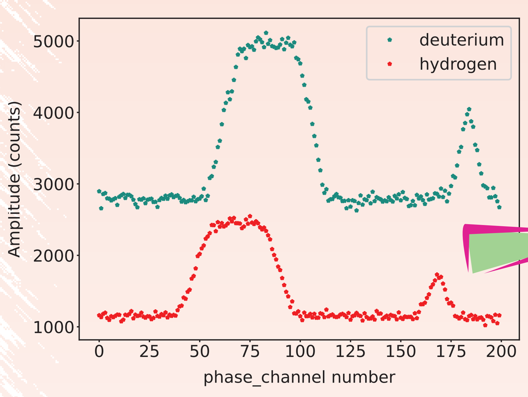


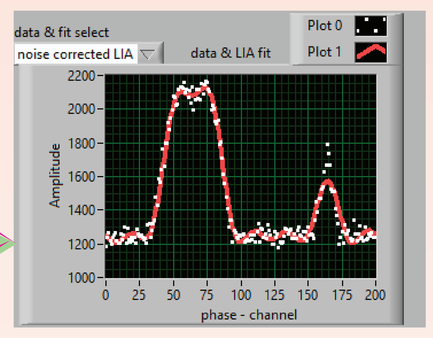
[Plot recieved from S. Rheinfrank]

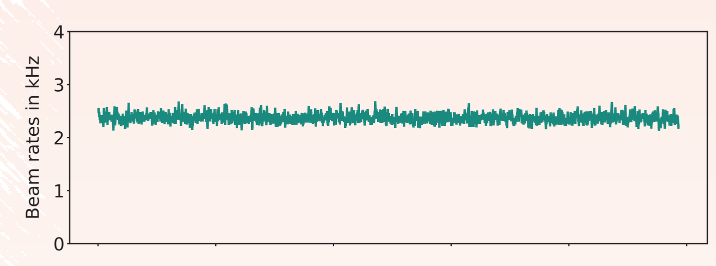
Preliminary Results

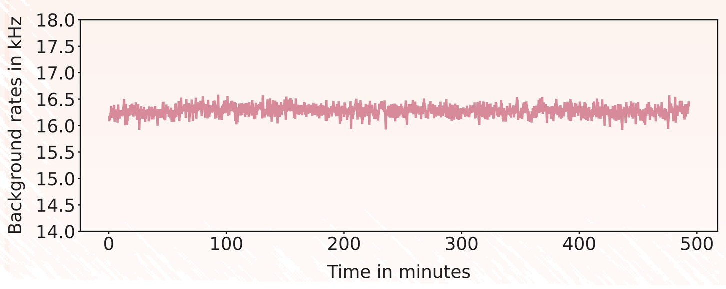
Transitions measured: σ_1 & σ_2

Extrapolation to 0 B-field: ±2 mA, ±6 mA, ±10 mA









Rising Set: σ_2 in negative currents, σ_1 in positive currents.
Falling Set: σ_2 in positive currents, σ_1 in negative currents.

Ideal transition frequencies:

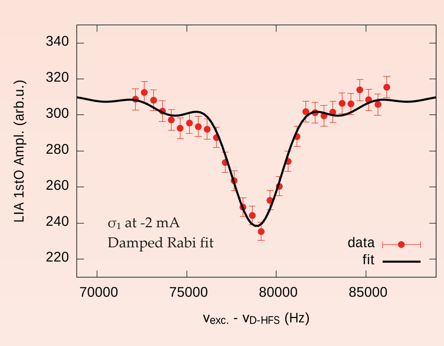
327 384 352.5222(17) Hz [5]

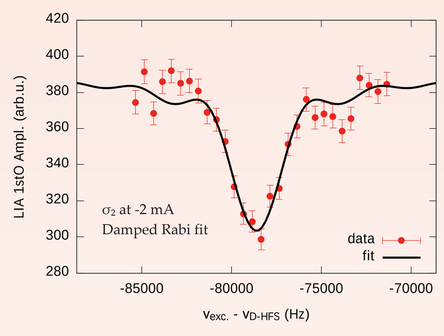
$$\nu_{\sigma_1} = \nu_D\sqrt{\left(1+\frac{2}{3}x+x^2\right)}$$

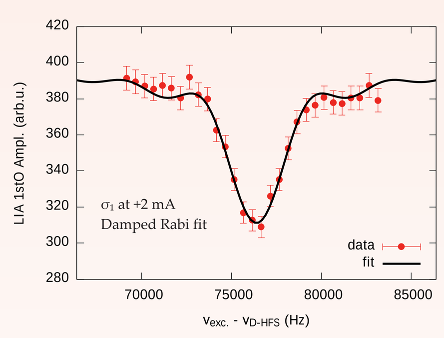
$$\nu_{\sigma_2} = \nu_D\sqrt{\left(1-\frac{2}{3}x+x^2\right)}$$

$$x = \frac{(g_J - g_I)\mu_0 H}{\nu_D}$$

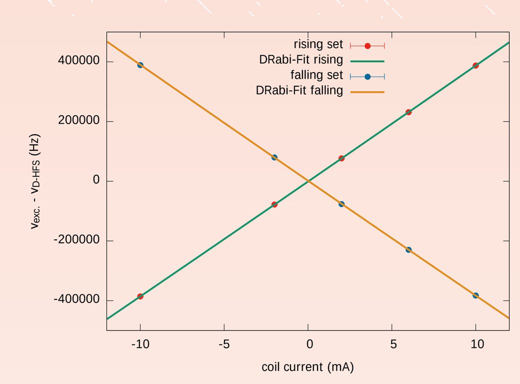
Magnetic Field; Electron g-factor; Nuclear gyromagnetic ratio in Bohr magnetons



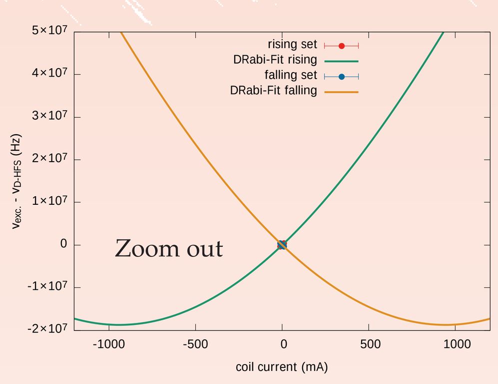




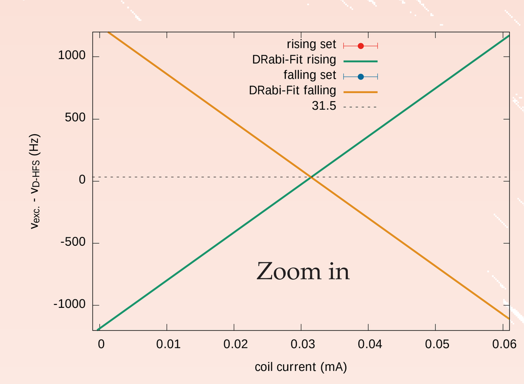
[5] D. J. Wineland and N. F. Ramsey, Phys. Rev. A **5**, 821, Feb 1972



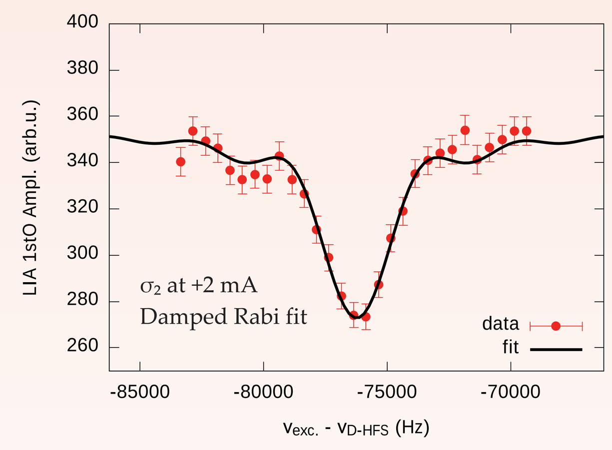
Merging the rising and falling data sets and fits to estimate the HFS splitting at zero B-field. Literature +31.5 Hz, ~ 100Hz error bar)



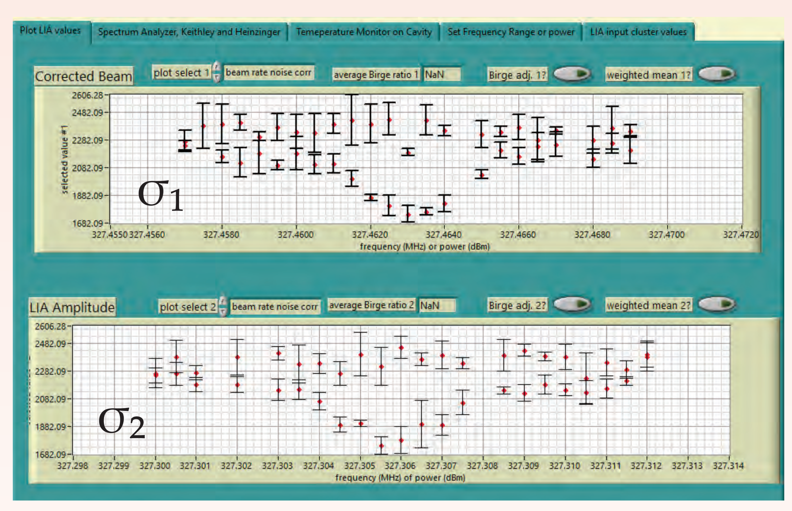
Extrapolation of fit function to around 1A, B-field ~ 4mT where σ_2 reaches minima.



Actual B-field is zero at 0.0315 mA. At zero current, background field ~ 0.13 μT.



Linewidth from preliminary fits ~1.7 - 2 kHz



Measurement for Sidereal Variation: Bkg - σ_1 - Bkg - σ_2 - Bkg 60 seconds: MW on, 30 seconds: MW off, 83 minutes per set. 117 sets, 12 kHz span per set, 500Hz steps, -2mA current, ~8.3 μT

Summary

1. Deuterium has strongly enhanced sensitivity to SME compared to hydrogen.
2. The most precisely measured transitions in Atomic Deuterium Maser[5] are not sensitive to SME.
3. A new spectrometer has been designed and commisioned for a Rabi type spectroscopy.
4. A deuterium beamline has been now set-up and is operational at LAC, Paris.
5. The experimental studies of sidereal variations in hyperfine transitions in deuterium have already begun.

Outlook

1. A detailed analysis for the first set of measurements will soon follow.
2. An additional data campaign starting next week or early June is foreseen.
3. A long term measurment would allow annual variation studies as well.
4. Publication of the associated PhD thesis by autumn this year.

Acknowledgements

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LABORATOIRE Aimé Cotton

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS