Searches for Lorentz violation in 3He/129Xe clock comparison experiments

F Allmendinger1, M Burghoff2, W Heil3,**[[1]](#footnote-1)** , S Karpuk3, W Kilian2, S Knappe-Grüneberg2, W Müller2, U Schmidt1, A Schnabel2, F Seifert2, Yu Sobolev3, L Trahms2, K Tullney3

1Physikalisches Institut, Universität Heidelberg, Heidelberg 69120, Germany

2Physikalisch-Technische Bundesanstalt, Berlin 10587,Germany

3Institut für Physik, Johannes-Gutenberg Universität, Mainz 55099, Germany

E-mail: wheil@uni-mainz.de

**Abstract:** We discuss the design and performance of a very sensitive low-field magnetometer based on the detection of free spin precession of gaseous, nuclear polarized 3He or 129Xe samples with a SQUID as magnetic flux detector. Characteristic spin precession times of up to 115 h were measured in low magnetic fields (about 1µT) and in the regime of motional narrowing. With the detection of the free precession of co-located 3He/129Xe nuclear spins (clock comparison), the device can be used as ultra-sensitive probe for non-magnetic spin interactions, since the magnetic dipole interaction (Zeeman-term) drops out in the weighted frequency difference, i.e., Δω=ωHe- γHe/γXe⋅ωXe. We report on searches for Lorentz violating signatures by monitoring the Larmor frequencies of co-located 3He/129Xe spin samples as the laboratory reference frame rotates with respect to distant stars (sidereal modulation).

1. Features of frequency standards and clocks

Since Galileo Galilei and Christiaan Huygens invented the pendulum clock, time and frequency have been the quantities that we can measure with the highest precision. Since 1967 the Cs atomic clock defines our unit of time, the second, as the period during which a cesium-133 atom oscillates 9,192, 631,770 number of cycles on the hyperfine clock transition  in the 62S1/2 atomic ground state. Cesium atomic clocks have been gradually improved to the point where modern cesium-fountain clocks realize the definition of the second with a relative uncertainty of about 1x10-15[1]. In the near future the cesium clock as the fundamental timing reference will be replaced with an optical clock, since the suppression of systematic effects that shift the frequency of a standard is greatly facilitated by the use of higher frequencies. Atomic systems under consideration include Al+, Hg+/2+ ,Sr, Sr+, etc. [2,3] .

In spite of the incredible high relative accuracy of frequency determination, the absolute accuracy of an atomic clock is poor, reaching 0.1 mHz under optimum conditions. To address fundamental questions in physics often associated with the experimental search for violation of fundamental symmetries in nature such as the violation of Lorentz invariance, much smaller frequencies or frequency shifts have to be traced. From that point of view it is more appropriate to develop a clock that oscillates at low frequencies (~ 10 Hz), but shows the same relative accuracy as a Cs atomic clock. Thus, frequency shifts in the pHz range caused by hypothetical interaction potentials will be accessible.

Clocks based on nuclear spin precession „spin clocks“ are the most promising approach to reach such sensitivity limits. The „spin clock“ described here is based on the detection of free spin-precession of gaseous, nuclear spin-polarized 3He or 129Xe samples [4]. Like in standard NMR, the free induction decay of the transverse magnetization is monitored and the Larmor frequency *f* of the precessing sample magnetization is related to the magnetic field B0 through, where γ is the gyromagnetic ratio of the corresponding nucleus. Since this type of clock will preferably operate at low magnetic fields and thus at low frequencies, using a SQUID as magnetic field detector is appropriate due to its high sensitivity in that spectral range. The 3He/129Xe nuclear spins are polarized by means of optical pumping [5,6]. Thus, the nuclear polarization obtained exceeds the Boltzmann polarization in typical NMR experiments by four to five orders of magnitude.

2. Co-located 3He/129Xe spin samples

Precision measurement of the Zeeman splitting in a two state system is important for magnetometry, as well as the search for physics beyond the standard model [7-13]. The most precise tests of new physics are often realized in differential experiments that compare the transition frequencies of two co-located clocks, typically radiating on their Zeeman or hyperfine transitions. The advantage of differential measurements is that they render the experiment insensitive to common systematic effects, such as uniform magnetic field fluctuations [12]. That’s why clock comparison experiments are often used to study fundamental symmetries of nature. In clock-comparison experiments, the Zeeman-term and thus any dependence on magnetic field fluctuations should drop out for the given combination of Larmor frequencies, i.e.,



(1)

For the 3He/129Xe gyromagnetic ratios we take the literature values [14,15] given by 2.75408159(20). The weighted frequency difference Δω or its equivalent, the weighted phase difference  compensates purely magnetic interactions but is sensitive to anomalous frequency shifts due to non-magnetic spin interactions of type



(2)

where the interaction can formally be written like the magnetic potential energy -μ⋅B . Examples of non-magnetic spin interactions that can be addressed by clock-comparison experiments are:

• Search for a Lorentz violating sidereal modulation of the Larmor frequency: 

• Search for a gravitoelectric dipole moment [16,17]: 

• Search for spin-dependent short-range interactions [18]: 

• Search for electric dipole moment (EDM) of Xenon [12]: 

According to the Cramer-Rao Lower Bound (CRLB) [19], the accuracy by which the frequency of a damped sinusoidal signal can be determined is given by



(3)

*SNR* denotes the signal-to-noise ratio, *fBW* the bandwidth, and *C(T,T2\*)* describes the effect of exponential damping of the signal amplitude with the transverse relaxation time *T2\**. For observation times *T ≤ T2\*,* *C(T, T2\*)* is of order one. Thus, the sensitivity of a co-located 3He/129Xe spin clock strongly depends on the observation time *T*. Deviations from the CRLB power-law (~*T-3/2*), due to noise sources inherent in the co-magnetometer have to be tested in Allan standard deviation plots used to identify the power-law model for the phase noise spectrum. We could show, that the noise of our 3He/129Xe spin clock is gaussian distributed at least up to observation times of T≈10000s [4] - one essential requirement the derivation of CRLB is based on.

In typical NMR experiments the transverse relaxation time () is of order *ms* only. Thus, the Fourier limit sets clear limits in the achievable accuracy of frequency measurement. The origin of this relaxation mechanism is the loss of phase coherence of the atoms due to the fluctuating magnetic field seen by the atoms as they diffuse throughout the cell (self-diffusion). Based on the Redfield theory of relaxation [20] due to randomly fluctuating magnetic fields, analytical expressions can be derived for the transverse relaxation rate for spherical and cylindrical sample cells, as reported in references [21,22], respectively. At low gas pressures (*p*), the regime of motional narrowing, and at low magnetic fields, the field gradient induced transverse relaxation rate for a spherical spin-sample cell of radius *R* is given by



(4)

*D* is the diffusion coefficient with *D~1/p* . Since we have  and from *SNR ∝ p*, it can be inferred that optimum conditions are met at magnetic fields around 1 μT (*fHe (Xe)* ≈ 10 Hz) and at gas pressures around 1 mbar for a spherical sample cell of radius *R* ~ 3-5 cm [4]. Including the longitudinal relaxation time *T1*, the general expression for the transverse relaxation rate *1/T2\** is . Long spin coherence times () of macroscopic samples are therefore essential to reach the *pHz* sensitivity range. As an example: For SNR=10000:1 in a bandwidth of 1 Hz, we obtain (using Eq.3) a measurement sensitivity of for an observation time of T=1 day ().

3. Basic layout of experimental setup

The instrumental setup is sketched in Figure 1. In our measurements, we use a SQUID vector magnetometer system, which was originally designed for biomagnetic applications inside the strongly magnetically shielded room BMSR-2 at PTB [23,24]. The sample cells are placed directly below the Dewar as close as possible to a SQUID sensor, which detects a sinusoidal *B* field change due to the spin precession of the gas atoms. Inside the μ-metal shielded room, a homogeneous magnetic field of about 400 nT was provided by two square coil pairs (Bx-coil and By-coil) which were arranged perpendicular (≤ 1mrad) to each other (see Fig. 1). The use of two coil pairs was chosen in order to manipulate the sample spins, e.g., π/2 spin-flip. The longitudinal relaxation time of Helium and Xenon in a cell made from low-relaxation GE180 glass [25-27] has been measured before in a conventional NMR setup to be *T1,He ≈ 160 h* and *T1,Xe ≈ 11 h*, respectively.



Fig.1 (Left) Horizontal cut view through building, shielded room and annex with data acquisition chamber and sample cell preparation area. The passive shielding factor of the BMSR-2 exceeds 108 above 6 Hz. With additional active shielding the room has a shielding factor of more than 7 × 106 down to 0.01 Hz. (Right): side view of inner room (2.9 × 2.9 × 2.9 m3) seen from the door opening. The pneumatically driven sliding door is indicated by a rectangle with thin dashed lines. The black rectangle is the Dewar housing the SQUIDs. The big open rectangles are the Bx- and By-coil pairs. The small circle below the Dewar shows the sample cell (fixation not shown). The (−x)-axis of the chosen coordinate system points at an angle of ρ = 280 to the north-south direction.

Fig.2a shows the magnetic flux density spectrum of a SQUID that measures the precession of 3He and 129Xe. The prominent features at about 4.7 Hz and 13 Hz correspond to the Larmor oscillation of the co-located 129Xe and 3He spins in one sample cell at a field of 400 nT. For frequencies *f* > 10 Hz, we find a white system noise of *ρsystem* ≈ 2.3 fT/√Hz. The cut-off frequency is at 125 Hz (sampling rate: *fsr* = 250 Hz). ‘Bumps’ and lines in the spectra at low frequencies are caused by mechanical vibrations or power line interference. Measured values for the *SNR* reach *SNR* ≈ 10000:1 in a bandwidth of 1 Hz, as can be inferred from Fig.2a. In Fig.2b, the measured signal amplitude of the precessing co-located 3He/129Xe spins is shown. The transverse relaxation times are extracted from the envelope of the decaying signal amplitudes for 3He and 129Xe with and at a gas mixture with pressures of 3He : 129Xe : N2 ≈ (2 : 8 : 35 ) mbar, typically. Nitrogen was added to suppress spin-rotation coupling in



Fig.2 a) Magnetic flux density spectrum of a low-Tc multiloop SQUID magnetometer inside BMSR-2 that measures the precession of 3He and 129Xe. b) Measured SQUID signal of the precessing co-located 3He/129Xe nuclear spins.

bound Xe-Xe van der Waals molecules [28]. Coherent spin precession can be monitored up to *T*=24 h, i.e., , still getting a *SNR* of *SNR* > 100:1. At present, the relatively short *T1,Xe* wall relaxation time of 129Xe limits the total observation time *T* of free spin-precession in our 3He/129Xe clock comparison experiments. Efforts to increase *T1,Xe*wall considerably are therefore essential.

4. Limit on Lorentz and CPT violation of the bound neutron using a free precession 3He/129Xe co-magnetometer

A great number of laboratory experiments have been designed to detect diminutive violations of Lorentz invariance. Among others, the Hughes-Drever-like experiments [29,30], have been performed to search for anomalous spin coupling to an anisotropy in space using electron and nuclear spins with steadily increasing sensitivity [31,32]. Lorentz violating theories should generally predict the existence of privileged reference systems. In contrast with the situation at the end of the 19th century, we have a rather unique choice nowadays for such a ”preferred inertial frame”, i.e., the frame where the Cosmic Microwave Background (CMB) looks isotropic. Trying to measure an anomalous coupling of spins to a relic background field which permeates the Universe and points in a preferred direction in spacetime as a sort of New Aether wind is a modern analogue of the original Michelson-Morley experiment. The theoretical framework presented by A. Kostelecky and colleagues parameterizes the general treatment of CPT- and Lorentz violating effects in a Standard Model extension (SME) [33].

To determine the leading-order effects of a Lorentz violating potential *V*, it suffices to use a non-relativistic description for the particles involved given by [34]

 (with: J = X, Y, Z ; w = e, p, n) . (5)

Like in [35,36], we search for sidereal variations of the frequency of co-located spin species while the Earth and hence the laboratory reference frame rotates with respect to a relic background field. The observable to trace possible tiny sidereal frequency modulations is the combination of measured Larmor frequencies (see Eq.1) and the weighted phase differences, respectively. In March 2009, we performed a measurement consisting of 7 runs in series, each with a duration of 13 hours at least.

The data of each run (*j*= 1,…,7) were divided into sequential time intervals *i* of length *τ* = 3.2 s (*i* = 1,…, *N*j) (see Fig.2b). The number of obtained sub data-sets laid between 14800 < *N*j < 18000 corresponding to observation times *T*j of coherent spin-precessions in the range of 13 h < *T*j < 16 h. For each sub data-set a χ2minimization was performed, using the fit-function

  (6)

with a total of 8 fit-parameters. Within the relatively short time intervals, the term (*c*0i + *c*lini⋅*t*) presents the adequate parameterization of the SQUID offset showing a small linear drift due to the elevated 1/*f*-noise at low frequencies (< 1 Hz) and some distinct distortions caused by mechanical vibrations. For each sub data-set we finally obtain numbers for the respective fit parameters including error bars. Therebyare given by. From these values the accumulated phases for each run *j* were determined and finally . Thus, one expects as a result a general phase offset ΔΦ(*j*)(*t*) =Φ(*j*)0 = const*.*, if no other drifts and noise sources come into play. Indeed, after subtraction of deterministic phase drifts like the linear phase shift ΦEarth = ΔωEarth⋅ tdue to Earth’s rotation, this results in phase residuals as shown in Fig. 3. Due to the exponential decay of the signal amplitudes, mainly that of Xenon with the much shorter *T*2\* of only 4h, the *SNR* decreases resulting in an increase of the residual phase noise, i.e., . Non-magnetic spin interactions - if they exist - would be felt in a temporal change of the phase residuals. In the last step, a piecewise fit function was defined, which is a combined fit to all seven runs, now including the parameterization of the sidereal phase modulation



(7)

ΩSD is the angular frequency of the sidereal day and *ϕSD* represents the phase offset of the sidereal modulation at the local sidereal time *tSD*=0.4053 (units of sidereal day) at the beginning *t0,1* of the first run with *ϕSD*=2π⋅*tSD*. From that, the RMS magnitude of the sidereal phase amplitude, yielding (2.25±2.29) mrad (95% CL) could be extracted [37]. This result is consistent with no Lorentz- and CPT-violating effects. In terms of the SME [34] we can express Φ*SD* according to

 (8)

*χ* is the angle between the Earth’s rotation axis and the quantization axis of the spins (*χ*=570). Within the Schmidt model, the valence neutron of 3He and 129Xe determines the spin and the magnetic moment of the nucleus. Thus, 3He/129Xe co-magnetometer is sensitive to the bound neutron parameter . With  GeV (95% CL) we have set an upper limit on neutron spin coupling to possible Lorentz and CPT violating background tensor fields.

5. Improvements

It is noticeable, that the uncorrelated error which represents the integrated measurement sensitivity of our 3He/129Xe co-magnetometer is about a factor of 50 less than the correlated one. The big correlated error on *as* and *ac* is caused by a piecewise similar time structure of and the sidereal phase modulation in the fit-function of Eq. 9. Therefore, the present sensitivity limit of our 3He/129Xe co-magnetometer is set by the *correlated* error. In order to substantiate that more clearly, we changed the fit-model of Eq. 9 by taking multiples of (), i.e., replacing TSD by . The results show that the correlated error approaches the uncorrelated one already for g ≥ 3 (see Table I). The uncorrelated error, however, is only marginally affected by this procedure, as expected.



TABLE I. Results for the sidereal phase amplitudes *ac* and *as* together with their correlated and uncorrelated 1σ-errors (2nd row) determined by a χ2-minimization using the fit model of (Eq. 7). In order to demonstrate the strong dependence of the correlated error on the angular frequency of the sidereal day , corresponding fit results are shown for multiples of: 

In March 2012, a new measurement run was performed at PTB-Berlin. The essential improvement there was the increase of the-time of Xenon, now reaching ~ 8h. With that, coherent spin precession could be recorded at least for 24 h. Furthermore, a gain of 2-3 in the *SNR* was achieved. A preliminary analysis of the data (Fig.3) shows the phase residuals after subtraction of phase drifts given by the fit-model of Eq. 9. The expected overall gain in sensitivity to a Lorentz violating interaction will be about a factor of 100, due to i) reduction of correlated error: ~7, ii) gain due to CRLB power-law (~1/T3/2): ~2.8, iii) gain in *SNR*: ~ 2-3, and iv) total data taking time 165 h (90 h March 2009 ): 1.8 . Thus, we should reach the sensitivity limit of  GeV (95% CL) in detecting a Lorentz violating sidereal frequency modulation as predicted, e.g., by string theories. In our low energy world, these effects will be strongly suppressed by the inverse powers of the Planck scale (MP ~ 1019 Gev/c2).Hence, as natural size we expect for SME-parameters like : . With , we will get sensititive to the 2nd order (m=2) Planck-scale suppression.

To summarize: 3He/129Xe co-magnetometry based on the detection of the free nuclear spin precession is a powerful tool to investigate fundamental symmetries in nature. The reason for such a high sensitivity is that free precessing 3He (129Xe) nuclear spins are almost completely decoupled from the environment. Therefore, this type of magnetometer is particularly attractive for precision measurements where long-term stability is required. We reported on our recent results on searches for a Lorentz violating sidereal modulation of the Larmor precession. The same method can be used to study parity and time-reversal symmetry-violating forces like in searches for spin-dependent short-range interactions induced by light, pseudoscalar bosons such as the axion invented to solve the strong CP problem as well as in searches for the electric dipole moment of 129Xe. And there is room for improvements: The limiting factor still is the relatively short wall relaxation time of Xenon. If similar numbers like for helium are achieved, then coherent spin precession of a macroscopic spin sample can be recorded over period of a week.

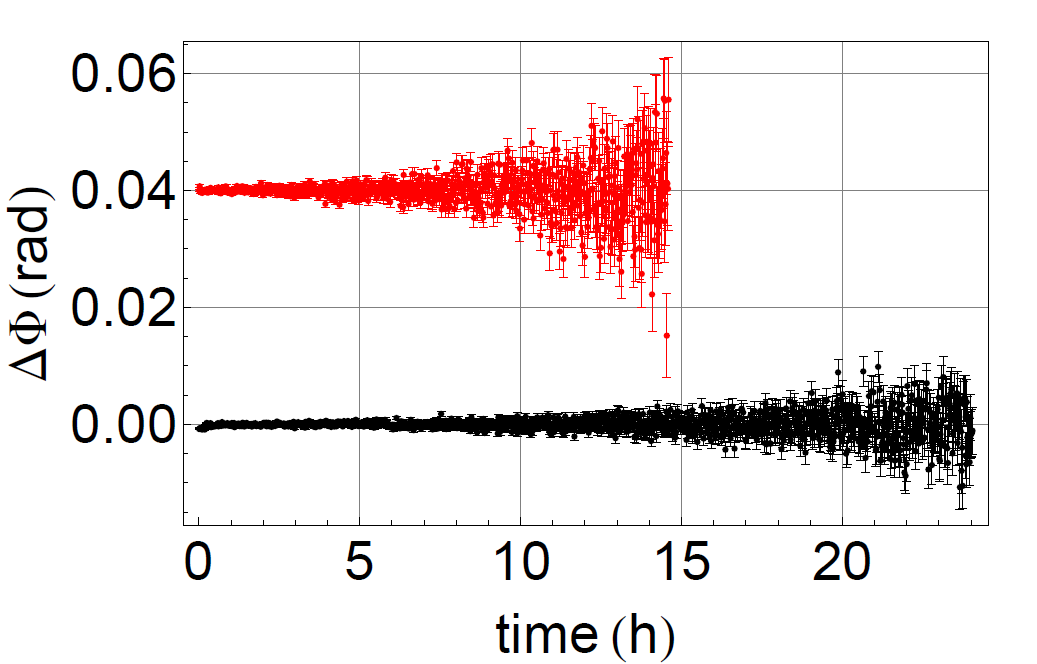


Fig.3: Phase residuals of the weighted phase difference *ΔΦ* (bandwidth: *fBW* = 0*.*125 Hz) after subtraction of deterministic phase drifts. The increase of the RMS of the phase noise with time is due to the exponential decay of the signal amplitudes, mainly that of Xenon. Comparison of phase residuals from a subrun in March 2009 (red; shifted by 0.04 rad) with those from March 2012 (black). The improvement of the  - time of Xenon by a factor of 2 () now allows data recording of coherent spin precession of at least 24 h. Also the signal-to-noise ratio could be increased by a factor 2-3.

References:

[1] S. Weyers, U. Hübner, R. Schröder, et al., Metrologia **38** 343 (2001)

[2] W.H. Oskay et al. , PRL **97** 020801 (2006)

[3] F. Riehle, *Frequency Standards*, WILEY-VCH, 2004

[4] C. Gemmel, W. Heil, S. Karpuk, et al., Eur. Phys. J. D **57** 303 (2010)

[5] G. Tastevin, et al., Appl. Phys. B **78**, 145 (2004)

[6] T. G. Walker and W. Happer, Rev. Mod. Phys. **69**, 629 (1997)

[7] V.W. Hughes, H.G. Robinson, V. Beltran-Lopez, Phys. Rev. Lett. **4** 342 (1960)

[8] J.D. Prestage, J.J. Bollinger, W.M. Itano, et al., Phys. Rev. Lett. **54** 2387 (1985)

[9] S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, et al., Phys. Rev. Lett. **57** 3125 (1986)

[10] T.E. Chupp, R.J. Hoare, R.A. Loveman, et al., Phys. Rev. Lett. **63** 1541 (1989)

[11] C.J. Berglund, L.R. Hunter, D. Krause, et al., Phys. Rev. Lett. **75** 1879 (1995)

[12] M.A. Rosenberry, T.E. Chupp, Phys. Rev. Lett. **86** 22 (2001)

[13] M.V. Romalis, W.C. Griffith, J.P. Jacobs, et al., Phys. Rev. Lett. **86** 2505 (2001)

[14] International council for Science: Committee on Data for Science and Technology (CODATA). www.codata.org (2007)

[15] M. Pfeffer and O. Lutz. J. Magn. Res. A, **108** 106 (2005)

[16] I. Yu. Kobzarev and L.B. Okun, JETP **16** 1343 (1963)

[17] B. Mashhoon, Lect. Notes Phys. **702** 112 (2006)

[18] S. A. Hoedl,\* F. Fleischer, E.G. Adelberger, et al., Phys. Rev. Lett. **106** 041801 (2011)

[19] S.M. Kay, Fundamentals of Statistical Signal Processing: Estimation Theory (Prentice Hall, New Jersey, 1993), Vol. I

[20] C.P. Slichter, Principles of Magnetic Resonance, 3rd edn. (Springer, Berlin, 1996)

[21] G.D. Cates, S.R. Schaefer, W. Happer, Phys. Rev. A **37** 2877 (1988)

[22] D.D. McGregor, Phys. Rev. A **41** 2631 (1990)

[23] A. Schnabel, M. Burghoff, S. Hartwig, et al., Neurology and Clinical Neurophysiol. **70** (2004)

[24] M. Burghoff, A. Schnabel, D. Drung, et al., Neurology and Clinical Neurophysiol. **67** (2004)

[25] J. Schmiedeskamp, W. Heil, E.W. Otten, et al., Eur. Phys. J. D **38** 427 (2006)

[26] A. Deninger, W. Heil, E.W. Otten, et al. , Eur. Phys. J. D **38** 439 (2006)

[27] J. Schmiedeskamp, H.-J. Elmers, W. Heil, et al., Eur. Phys. J. D **38** 445 (2006)

[28] B. Chann, I.A. Nelson, L.W. Anderson, et al., Phys. Rev. Lett. **88** 113201 (2002)

[29] V. W. Hughes, H.G. Robinson, and V. Beltran-Lopez, Phys. Rev. Lett. **4** 342 (1960)

[30] R.W.P. Drever, Philosophical Magazine, **6** 683 (1961)

[31] S.K. Lamoreaux, et al., 1986 Phys. Rev. Lett. **57** 3125 (1986)

[32] J.M. Brown, et al., Phys. Rev. Lett. **105** 151604 (2010)

[33] D. Colladay and V.A. Kostelecký, Phys. Rev. D **58** 116002 (1998)

[34] V.A. Kostelecký and C.D. Lane, Phys. Rev. D **60** 116010 (1999)

[35] D. Bear, et al., Phys. Rev. Lett. 85 5038 (2000)

[36] J. M. Brown et al. Phys. Rev. Lett., 105, 151604 (2010)

[37] C. Gemmel C, W. Heil, S. Karpuk, et al., Phys. Rev. D 82 111901 (2010)

1. corresponding author [↑](#footnote-ref-1)