Application of a He-3 magnetometer: Search for Lorentz- and CPT violation

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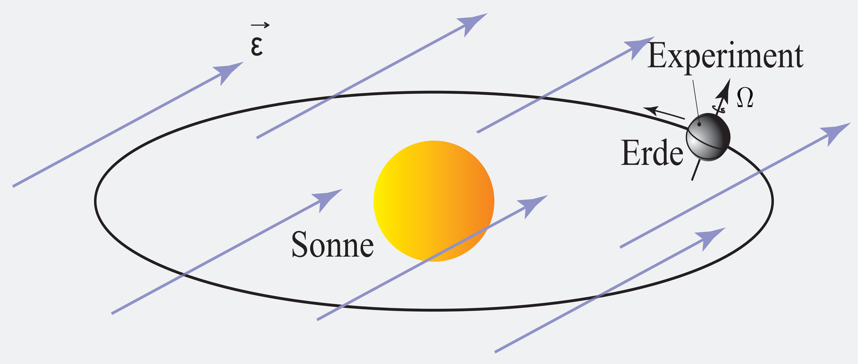
Theoretical Motivation



With a clock comparison test the Lorentz Invariance of the Theory of Relativity can be checked experimentally. For this test, we search for a possible dependence of clock frequency of an atomic clock on its orientation.
Our atomic clock is the free precession of polarized Helium-3 in a constant magnetic field $\vec{B}$. An orientation dependence of the clock frequency can be written as a coupling to a background field $\vec{\varepsilon}$, then the Hamiltonian is given by:

$$H = -\vec{\mu}\cdot\vec{B} - \beta\vec{\sigma}\cdot\vec{\varepsilon}$$

The precession frequency is then given by

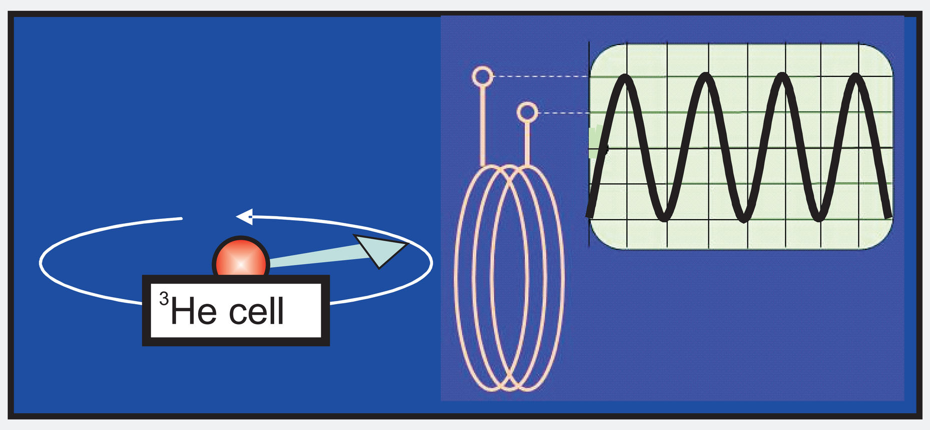
$$\nu = 2\mu B + 2\beta\cos\left(\vec{\varepsilon},\vec{B}\right)$$

and changes with the time of the sidereal day as the clock moves with the surface of the earth.
The commonly used parametrization of Lorentz-Violating Effects from Kosteleczky et al. allows to compare the sensitivity of different experiments. It also shows that Lorentz-Violation is likely accompanied by CPT violation.

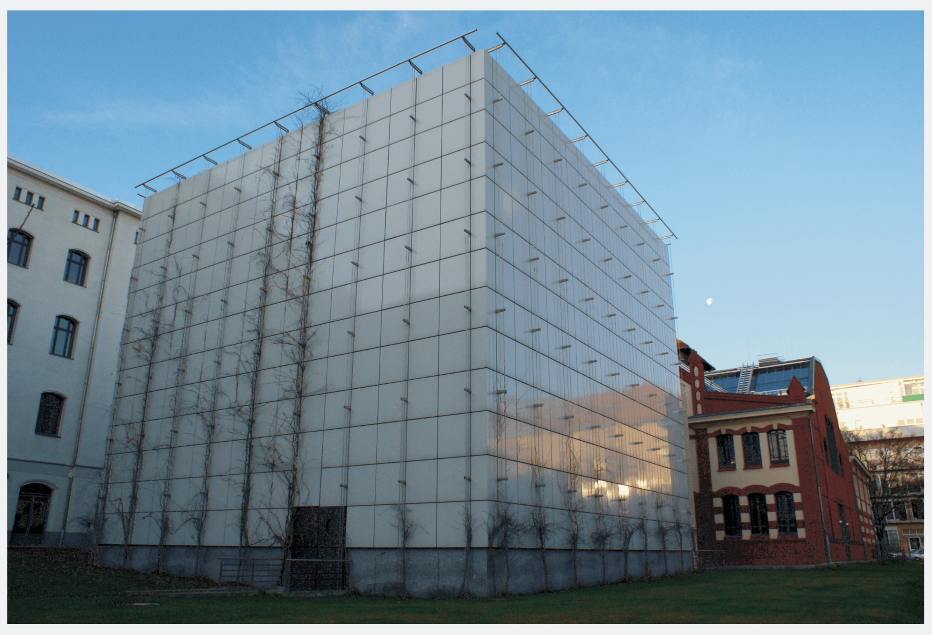
Basic principle of the measurement

Our idea: Use the free precession of polarized ^{3}He gas in a glass cell as an atomic clock. Its frequency is given by the magnetic field and the contribution of a possible Lorentz-Violating effect.

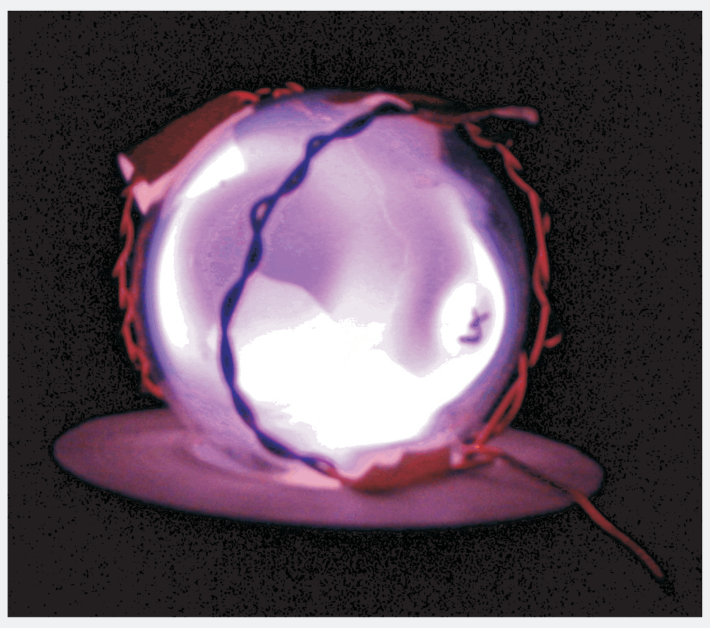
* Main reason to use ^{3}He:
  - longitudinal (T_1) and transverse (T_2*) relaxation times can be made very long (> 100 h)
  - ^{3}He nuclear Polarization can be made very high, reaches $P_{He} \sim 80\%$
* Precession frequency only depends on the magnetic field; no systematic effects due to light shifts, feedback etc.
* Detection of Spin Precession by means of SQUIDs. Sensitivity $\sigma_{B,SQUID} \sim 4.5\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$
* Expected signal strength for a spherical cell (p_{He} = 5 mbar, P_{He} = 30%):
  $B_{rot} \sim \frac{\mu_0}{4\pi}\cdot\frac{2M}{r^3} \sim 30$ pT @ $r = 5$ cm (distance from the cell center)
* Longitudinal Relaxation Time T_1:
  $$\frac{1}{T_1} \sim \frac{1}{T_{1,\mathrm{Wall}}}$$
* Transverse Relaxation Time T_2*:
  $$\frac{1}{T_2^*} = \frac{1}{2T_{1,\mathrm{wall}}} + \frac{8\gamma^2R^4}{175D}\left[\left(\frac{\partial B_z}{\partial x}\right)^2 + \left(\frac{\partial B_z}{\partial y}\right)^2 + \left(\frac{\partial B_z}{\partial z}\right)^2\right] + D\cdot\frac{|\nabla B_x|^2 + |\nabla B_y|^2}{B_0^2}\cdot\frac{1}{\left(x_{11}^2-2\right)\left(1+D^2x_{11}^4/\gamma^2B_0^2R^4\right)}$$
  Here D is the diffusion coefficient, R is the cell radius, $x_{11} = 2.08$
* Estimated value:
  $T_2^* \sim 100$ h @ absolute magnetic field gradient of some pT/cm, $B_0 \sim 1\mu$T



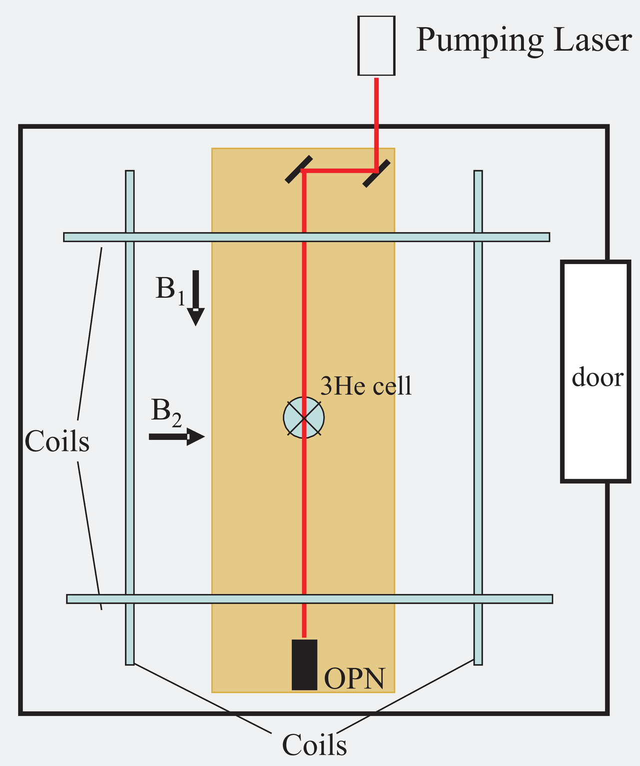
Our first experimental setup at the PTB Berlin



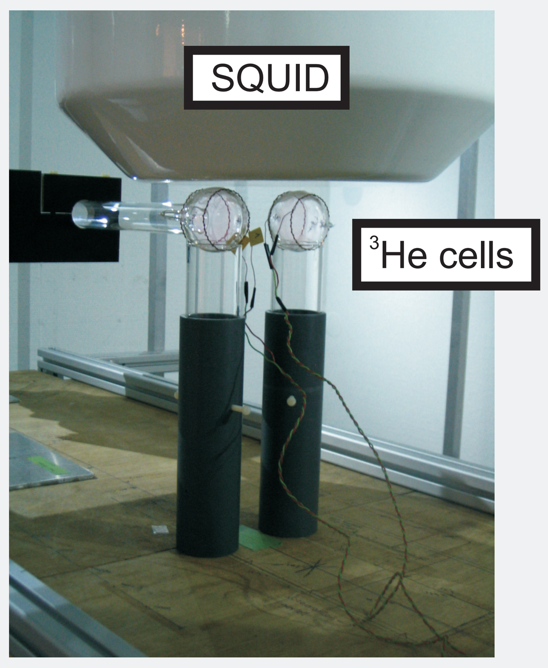
BMSR-2: Anti-Magnetic Screen (PTB Berlin)
8 layers of μ-metal, HF shielding
rest field: 400 pT
gradient in rest field: several pT/cm in a volume of ~ 2 m^3



* Glass cell filled with ^{3}He at p = 5 mbar
* Material: aluminosilicate glass Ge180
* Size: 6 cm diameter
* Gas discharge needed for Metastability Exchange Optical Pumping (MEOP)



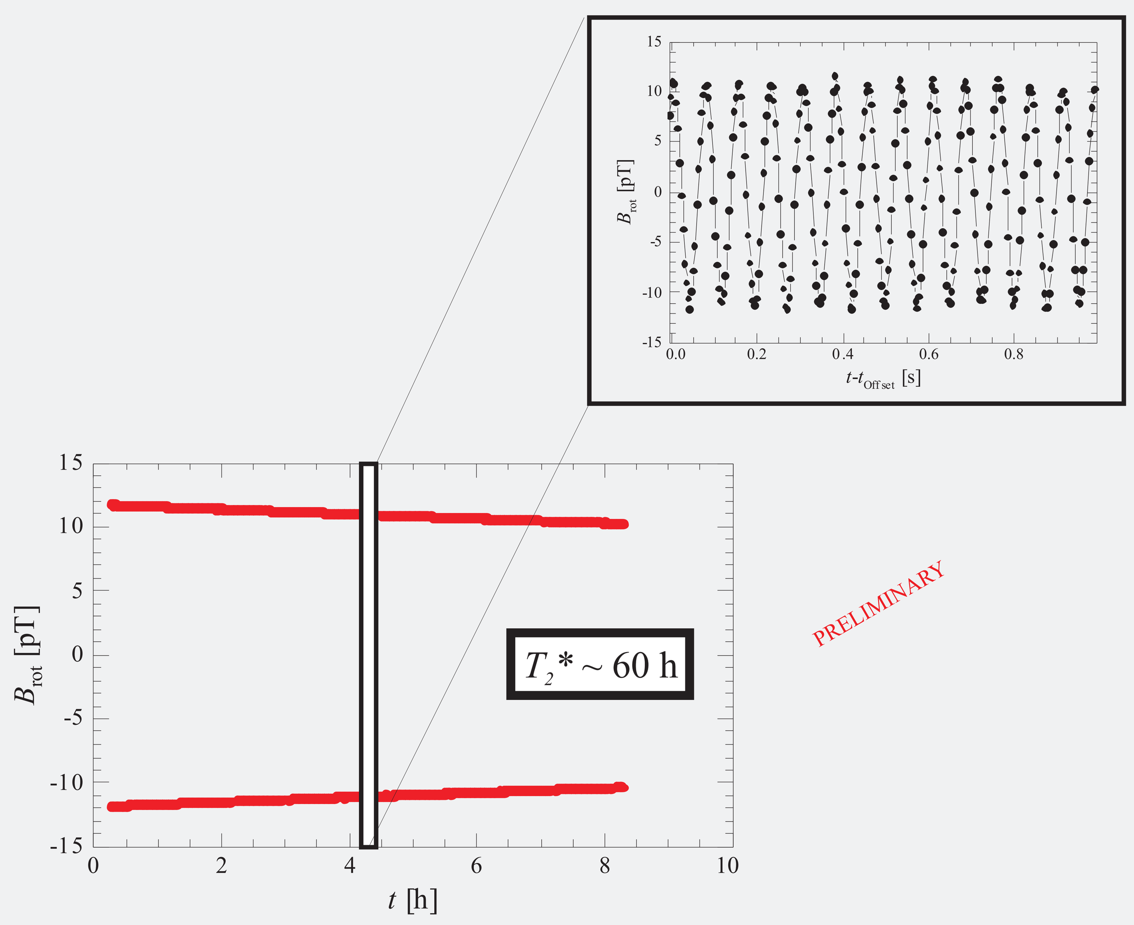
Principle of the experiment:
* ^{3}He gas is polarized by MEOP along B_1
* Non-Adiabatic Field Switch (π/2 flip)
* Spin precession around B_2



Detection of the free precession signal using a Low-T_c SQUID gradiometer.
In the picture, two cells were used to measure the magnetic field gradient between the cells.

Measurement of Precession

Two SQUIDS which are combined to form a gradiometer in order to decrease the background. The difference of the two is our signal. In a setup with one cell we get:



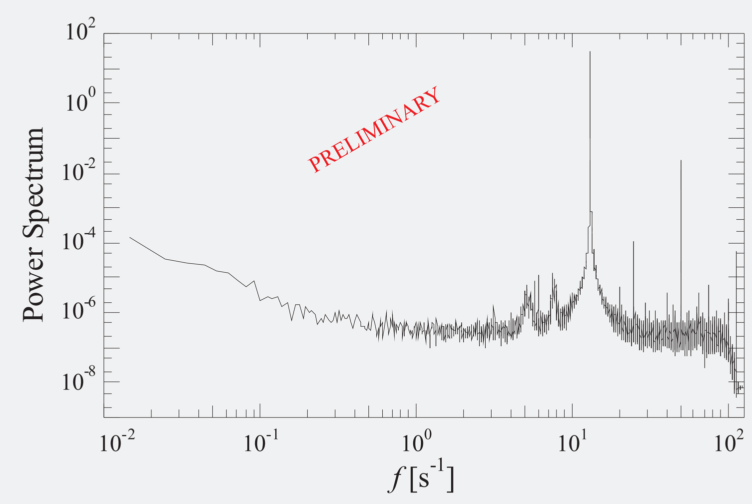
Measured signal strength:
$B_{rot} \sim 13$ pT
Extracted transverse relaxation time T_2*:
$T_2^* \sim 60$ h

Statistical Sensitivity

The statistical precision is given by the so-called Cramér-Rao-Lower Bound, which is for a pure sinusoidal signal and white noise:

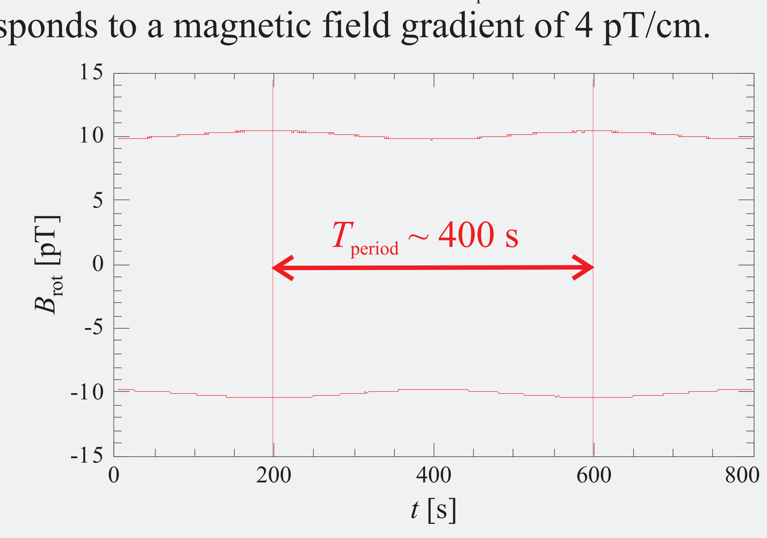
$$\delta B = \frac{\sqrt{6}}{\gamma_{He}\cdot\pi\cdot SNR}\cdot\frac{1}{\sqrt{T^3}}$$

With a SNR of about 3000/√Hz a field sensitivity of 1 fT is reached within $T \sim 100$ seconds.



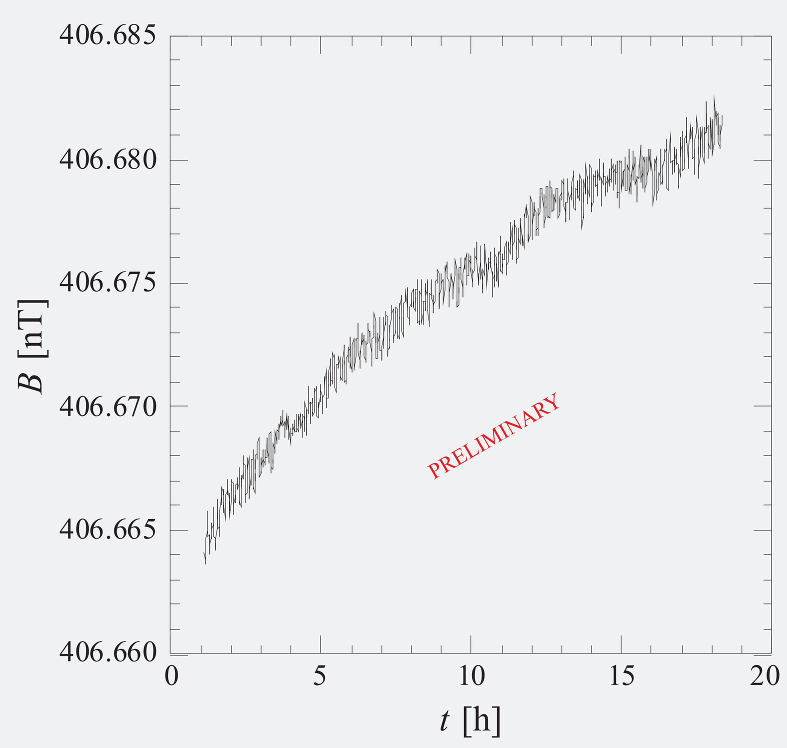
Measured Field Gradient

Measurement with 2 cells at a distance of 17.5 cm allow gradient measurements. The result, $T_{period} \sim 400$ s, corresponds to a magnetic field gradient of 4 pT/cm.



Magnetic field drifts and Comagnetometry

The variation of the measured magnetic field with time is shown in the picture below. We find that we have a magnetic field drift of about 1 pT/h. This number was independently confirmed in a direct measurement with the SQUID.



Problem: Magnetic field drift in BMSR-2 still too high.
Solution:
* Use of a comagnetometer (^{3}He, ^{129}Xe in the same volume)
* ^{3}He, ^{129}Xe simultaneously pumped by spin exchange optical pumping (SEOP)
* T_2*(^{129}Xe) of 8000 s already demonstrated (Kilian et al.)
  → improvements needed
* Alternative: ^{3}He, ^{133}Cs comagnetometer: A very sensitive cesium magnetometer has been developed in the group of A. Weis at U. Fribourg. We don't expect the helium and the cesium to influence each other.