Abstract: In the low energy regime, precision measurements of spin precession have gained increased attention as an alternative pathway to physics beyond the standard model. These measurements aim at the detection of minute frequency changes superimposed on low Larmor frequencies at extremely weak magnetic fields. Such measurements require an effective shielding against the magnetic field of the Earth and other perturbations. For measuring the precession frequency with high precision, a long lifetime of the precessing nuclear magnetization is required, thus the homogeneity of the applied field is a crucial parameter. In addition, criteria are needed that unambiguously distinguish magnetic artifacts from the non-magnetic exotic interactions that we search for. This can be accomplished by the concept of co-magnetometry, i.e., by simultaneous measuring the precession of two nuclear species such as $^3$He and $^{129}$Xe. Yet another kind of co-magnetometry is the use of SQUIDs for monitoring the spin precession. SQUIDs are magnetic field detectors of their own kind, which can measure the oscillating magnetic field generated by the precessing nuclear magnetic moment as well as the magnetic dc background field. In this presentation, I will report on the current state of the art in our lab in measurements of nuclear spin precession of noble gases.
Outline

Experimental Set-up
  Magnetic shielding
  SQUIDs
  Field homogeneity
  $^{3}\text{He}$.-$^{129}\text{Xe}$-Comagnetometry

Search for non-magnetic interactions
  XeEDM
  Short range interaction
  Lorentz-Invariance Violation

Axion wind
  SQUID based Comagnetometry
Experiment: Magnetic shielding

Berlin Magnetically Shielded Room - 2

Shielding factor vs. frequency

Residual static field < 1 nT
Experimental: Magnetic shielding

Helmholtz-Coils inside BMSR-2

\[ \sim 1 \mu T \quad + \quad < 1 nT \]
Experimental: Magnetic shielding

Helmholtz-Coils inside BMSR-2

Dewar filled with liquid He

Glass bulb filled with hyperpolarized $^3$He and/or $^{129}$Xe
Helmholtz-Coils inside BMSR-2

Dewar filled with liquid He

Glass bulb filled with hyperpolarized $^3\text{He}$ and/or $^{129}\text{Xe}$
Experimental: Field homogeneity

3He precession as measured by SQUID

SQUIDs
SQUID signal in a field of $\sim 2\mu T$
after closing the door of the BMSR-2

Drifts of $\pm 0.3 \, \text{pT}$

Closing the door
Experimental: Co-magnetometry

SQUID signal in a field of ~ 2μT after closing the door of the BMSR-2

Drifts of ±0.3 pT

Closing the door
Experimental: Co-magnetometry

Co-magnetometer:

\[ \Delta \omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \omega_{Xe} = 0 \ ? \]

In real experiments \( \Delta \omega \) is not zero, because:

- uncertainties in \( \gamma_{He}/\gamma_{Xe} \):

\[ \gamma_{He}/\gamma_{Xe} = 2.7540816 \pm 0.0000002 \]

For \( \gamma_{Xe} = 4 \) Hz this may cause a constant drift of up to \( \Delta \omega = 3 \, \mu \text{rad/s} \)
In real experiments $\Delta \omega$ is not zero, because:

- uncertainties in $\gamma_{\text{He}}/\gamma_{\text{Xe}}$
- Earth rotation:
  
  The lab frame is a rotating frame!

$\Delta \omega_{\text{rot}} = \Omega_{\text{Earth}} \left(1 - \frac{Y_{\text{He}}}{Y_{\text{Xe}}} \right) \cos \theta \cos \vartheta$

$= 68.7263 \, \mu\text{rad/s}$

geograph. latitude
bearing of $\mathbf{B}$
Experimental: Co-magnetometry

\[ \Delta \omega = \omega_{He} - \frac{Y_{He}}{Y_{Xe}} \omega_{Xe} = 0 \]

Search for a variation in \( \Delta \omega \)
Search for exotic interactions

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Search for $^{129}$XeEDM

$\Delta \chi = \hbar \chi \left( \frac{\chi_1 + \chi_2}{\chi_1} \right) = 4 \cdot E \cdot |d_{12}|$

$\Delta \omega = \Delta \omega_{N,EDM} - (\frac{\omega_{N}}{\omega_{EDM}}) \cdot \Delta \omega_{EDM}$

$\Delta \omega_{N,EDM} = (\frac{\omega_{N}}{\omega_{EDM}}) \cdot \Delta \omega_{EDM}$
Search for axions

Tullney et al. (2013) PRL
Axion wind

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SQUIDs

\[ v = v_{\text{Larmor}} \]

Axion wind

Larmor frequency of the noble gas nucleus ($^3$He or $^{129}$Xe): $v_L$

Frequency of the axion like particle: $v_{\text{ALP}}$
Axion wind

Signatur of a magnetic artifact (if $v_{\text{art}} < v_L$):

- fourth peak at $v_{\text{ext}}$

\[ v_{\text{art}} \quad v_{\text{ext}} \quad v_L \]

\[ v_{\text{art}} + v_{\text{art}} = v_L + v_{\text{art}} \]
Axion wind

Alternative Situation: \( v_L < v_{\text{ALP}} \)

Reflection at zero results in doublet \( \pm v_L \) around \( v_{\text{ALP}} \)
Axion wind

Signatur of a magnetic artifact

--- fourth peak at \( v_{\text{art}} \)

\[
\begin{align*}
&V_{\text{art}} \\
&V_{\text{art}} - V_1 \\
&V_{\text{art}} - 2V_1 \\
&V_1 + V_{\text{art}}
\end{align*}
\]
Axion wind

From our experimental data we can estimate the range of amplitudes and frequency where interactions can be detected by our current set-up.
Axion wind

Optimistic outlook:
Increase He-Amplitude
Reduce noise
Decrease distance

\[ B_{\text{mod}} / \text{fT} \]

\[
\begin{align*}
7 \text{ pT} & \quad \rightarrow \quad 100 \text{ pT} \\
2 \text{ fT/Hz} & \quad \rightarrow \quad 0.5 \text{ fT/Hz} \\
58 \text{ mm} & \quad \rightarrow \quad 28 \text{ mm} \\
\rightarrow & \quad \sim \times 200
\end{align*}
\]

Modulation frequency \( \nu_{\text{mod}} / \text{Hz} \)

Possible measurement range:

- 0.00001 to 1
- 1 to 10
- 10 to 100
- 100 to 1000
- 1000 to 10000
- 10000 to 100000
- 100000 to 1000000
- 1000000 to 10000000
- 10000000 to 100000000
- 100000000 to 1000000000

- 0.001 to 0.01
- 0.01 to 0.1
- 0.1 to 1
- 1 to 10
- 10 to 100
- 100 to 1000
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- 1000000 to 10000000
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June 19th, 2014

New Ideas in Low Energy Tests of Fundamental Physics
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