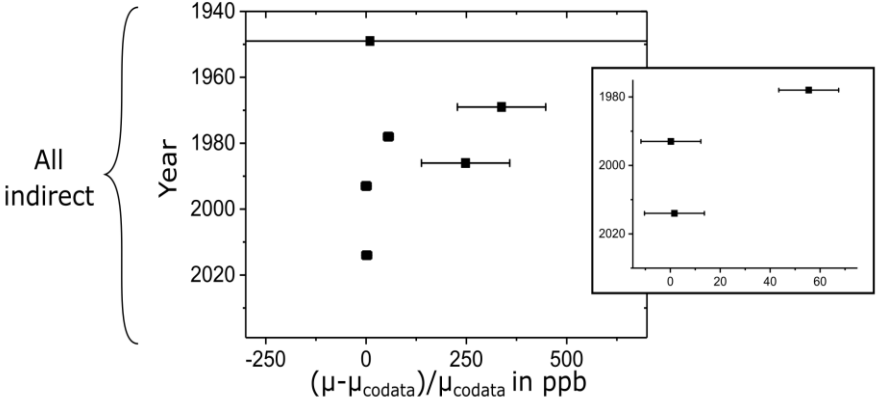
High-precision measurement of the HFS of $^3He^+$ in a Penning trap

A. Schneider, B. Sikora, S. Dickopf, M. Müller, N. Oreshkina,
A. Rischka, I. Valuev, S. Ulmer, J. Walz, Z. Harman,
C. Keitel, A. Mooser, K. Blaum

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Motivation

First direct high-precision measurement of ^{3}He nuclear magnetic moment with ppb precision



Previous measurements:

- Comparisons of ^{3}He and H_2O or H_2 probe only
- μ_{He} known to $1.2*10^{-8}$ only

  limited by knowledge of shielded proton magnetic moment

Rudzinski A., et al. *J.Chem. Phys.* **130** 244102 (2009)

Nikiel A., *et al.* Eur. Phys. J. D **68** 330 (2014)

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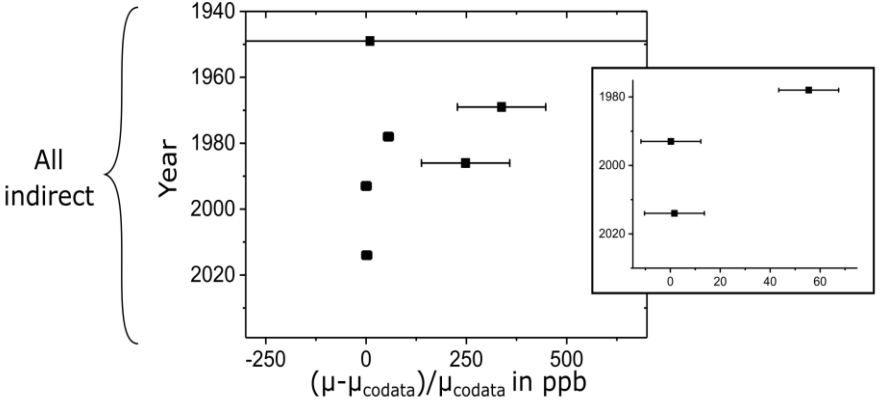

Establish hyper-polarized ^{3}He NMR probes as independent standard for precision magnetometry

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	Water NMR		^{3}He
Dependence on temperature	1	>	1/100
Dependence on probe shape	1	>	1/1000
Diamagnetic shielding	1 measured	>	1/10 calculated

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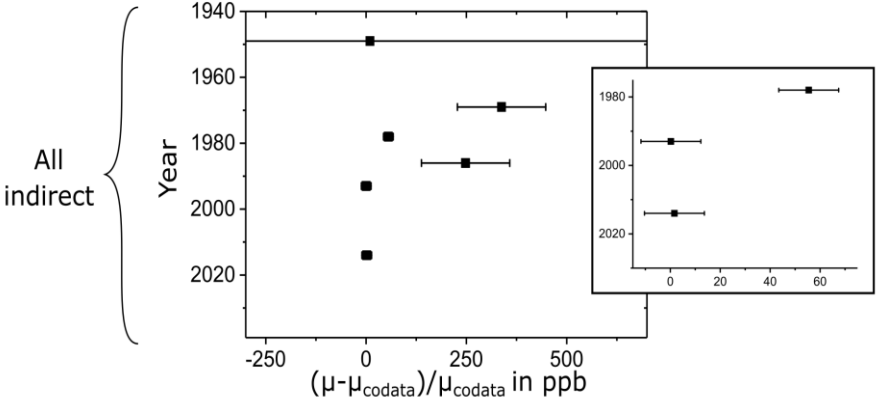

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➡ Application: muon g-2

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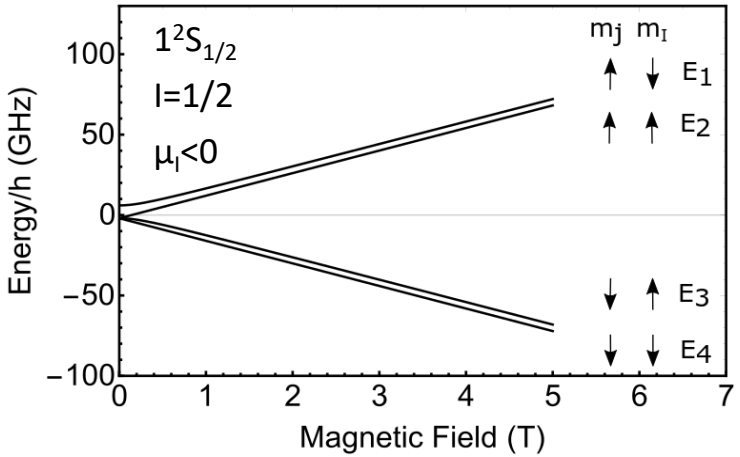


Zero-field splitting:

$$\Delta E^{HFS} = E^F(1 + \delta^{QED} + \delta^{rec} + \delta^{str} + \delta^{nucl})$$

with Fermi contact energy E^F

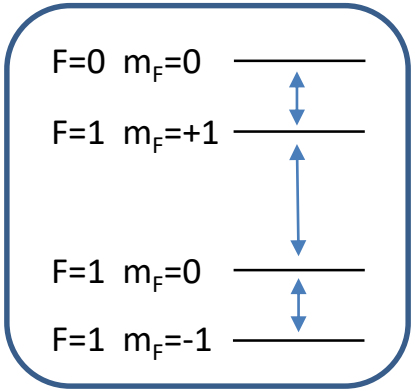
➡ determination of e.g. nuclear structure effect δ^{nucl}

ΔE^{HFS} known to 1.1 ppb (Schuessler et al., Phys. Rev. **187** 5 (1968))

We aim for measurement of order 10ppt

Magnetic Moments in Penning Traps

Determination of energy splitting between spin-states



$\omega_{F=I\pm\frac{1}{2}}(g_I, g_j, \Delta E^{HFS}, B)$

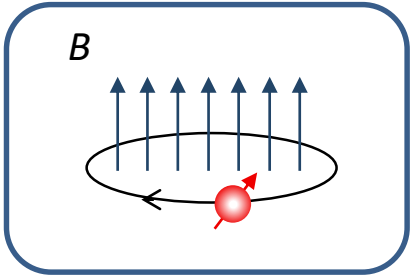
$^3He^+$

$1^2S_{1/2}$

I=1/2

$\mu_I<0$

Simultaneous cyclotron frequency measurement



$$\omega_c = \frac{e}{m_{He}} B$$

B-field independent measurement of g_I,g_j and ΔE^{HFS}

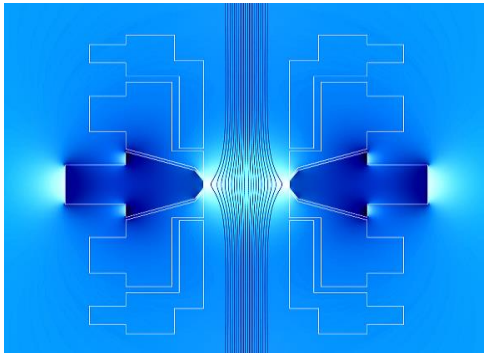
Detection of Spin-State - Continuous Stern-Gerlach Effect

Magnetic field inhomogeneity

$$B_z = B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)$$

⇒ axial frequency dependent on magnetic moment

Ring electrode made of CoFe



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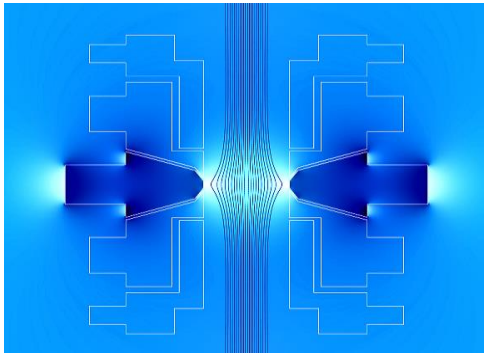
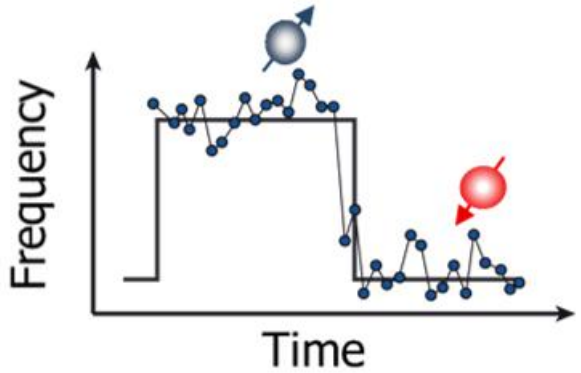


Spin-transition induces frequency jump



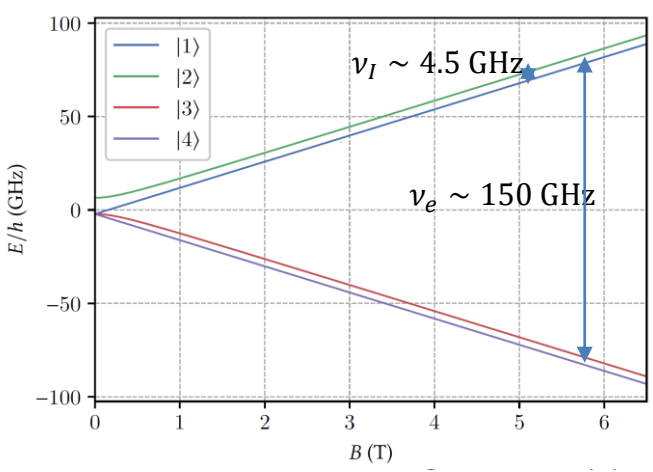
$\Delta\nu_{z,SF} \sim \mu/(qm)^{1/2}$

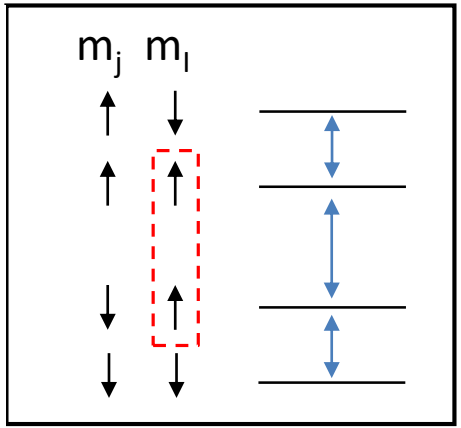
$\Delta\nu_p/\Delta\nu_e = 10^{-4}$

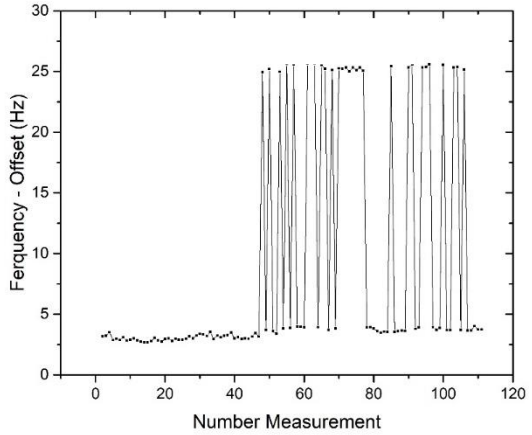
$\Delta\nu_{He}/\Delta\nu_p = 0.3$

Spin-State Detection $^3He^+$

$\Delta\nu_{z,SF}$ of $20Hz$, much easier to detect compared to 90mHz

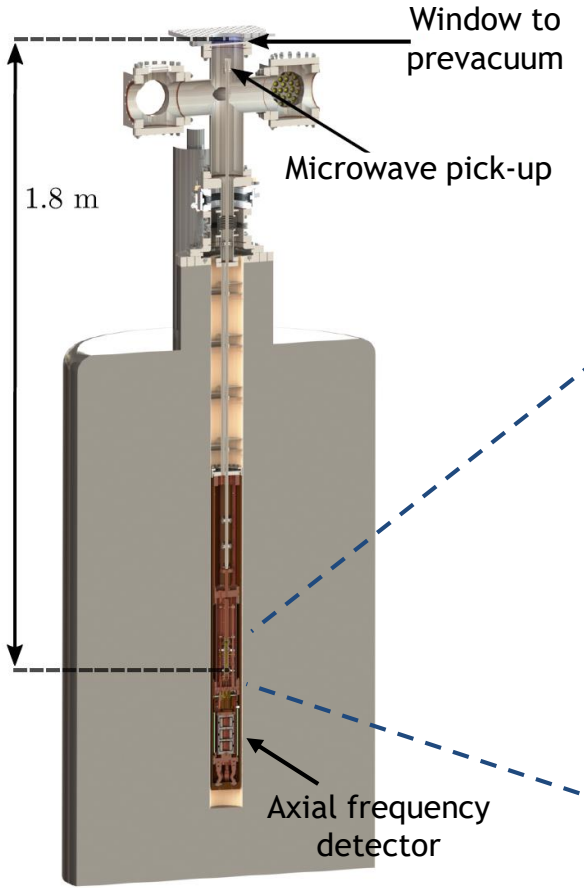


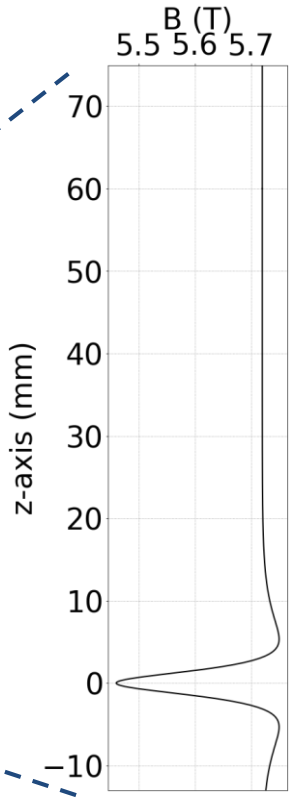


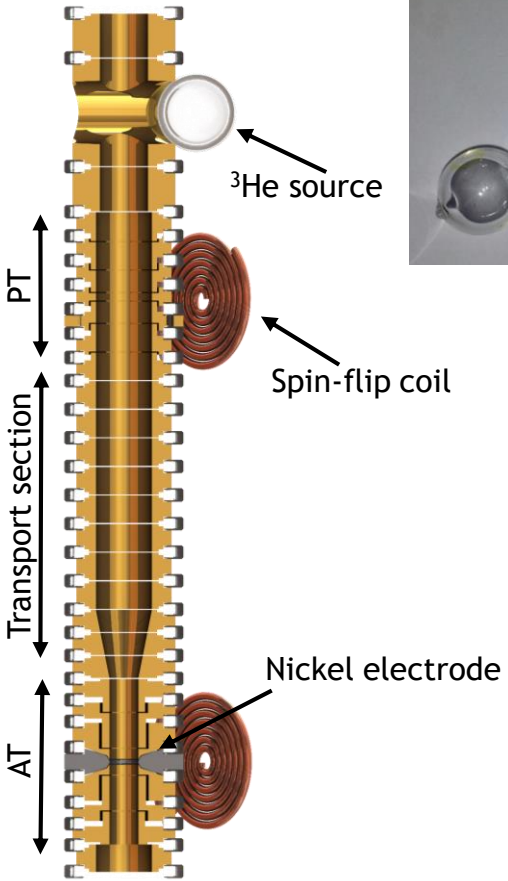


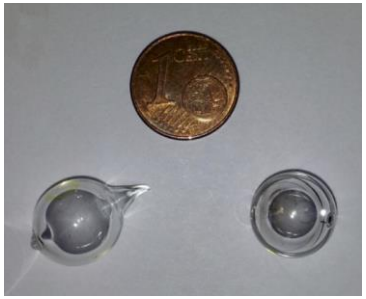
Map readout of nuclear spin-state onto detection of electronic transitions

Setup

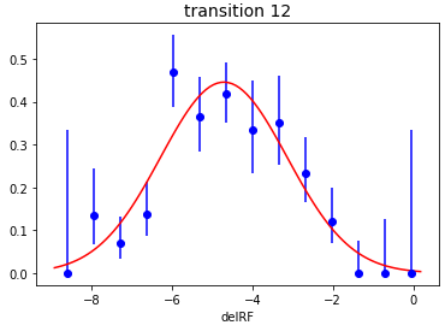

Window to prevacuum
Microwave pick-up
1.8 m
Axial frequency detector

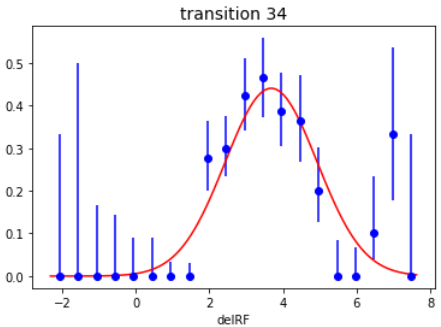

B (T)
5.5 5.6 5.7
z-axis (mm)
70
60
50
40
30
20
10
0
−10

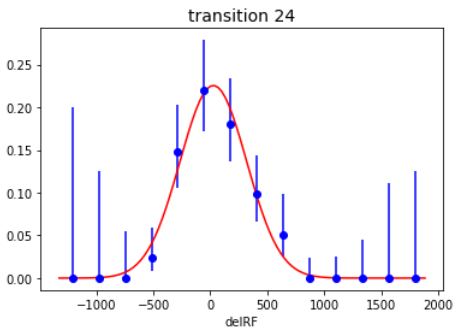

^{3}He source
PT
Spin-flip coil
Transport section
Nickel electrode
AT

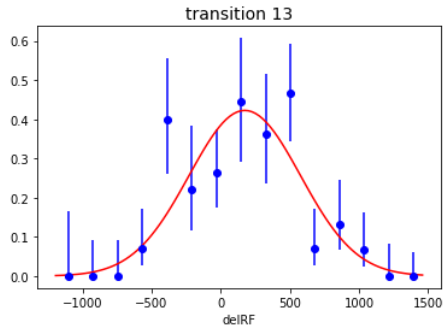


Results









	Relative uncertainties
g_e	3e-10
g_I	8e-10
E_{HFS}	2e-11

Summary

Motivation:

- Calibration for ^{3}He NMR probes independent of water probes
- Check of theoretical shielding by combing $^3He^{2+}$ and $^3He^{+}$ measurements
- Determination of nuclear structure effects

$^3He^{+}$ measurement:

- Avoid direct nucl. SF detection by mapping the nucl. state on the electronic transitions
- Measured four HFS transitions

Next steps:

- Building new setup for $^3He^{2+}$ *g*-factor measurement
- requires sympathetic laser cooling to allow nucl. spin-state detection