MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Direct measurement of the $^{3}He^{+}$ magnetic moments

Stefan Dickopf[1], Marius Müller[1], Natalia S. Oreshkina[1], Alexander Rischka[1], Antonia Schneider[1], Bastian Sikora[1], Igor Valuev[1], Stefan Ulmer[2], Jochen Walz[3,4], Zoltan Harman[1], Christoph H. Keitel[1], Andreas Mooser[1], Klaus Blaum[1]

1 - Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

2 - RIKEN, Ulmer Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan

3- Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, D-55128 Mainz, Germany

4 - Helmholtz-Institut Mainz, Staudingerweg 18, D-55128 Mainz, Germany

RIKEN

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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Motivation

First high-precision measurement of the $^3He^+$ hyperfine structure and direct measurement of the helion *g*-factor

g_e (bound-state electron *g*-factor)

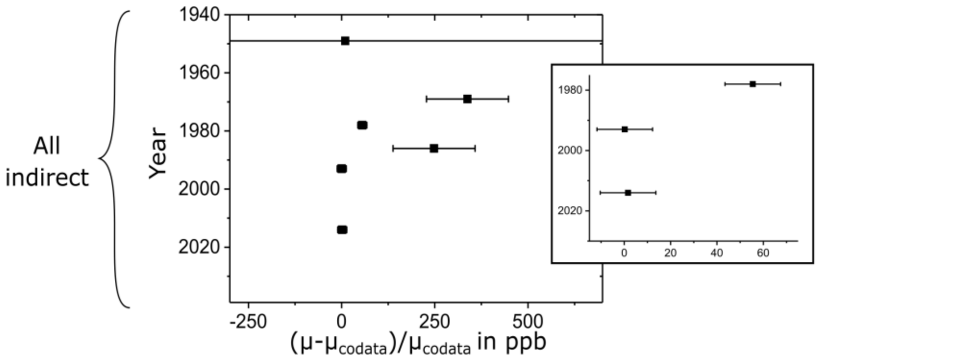
- Comparison with theory value $\delta g_{e,theo} / g_{e,theo} \sim 10^{-13}$

g_I (shielded nucleus *g*-factor)

- Currently only comparisons of ^3He with H_2O or H_2 probe only
- Establish ^3He NMR probes for accurate magnetometry

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

- Application: muon *g*-2 experiment



Past, indirect measurements of the nuclear magnetic moment

ΔE_{HFS} (zero-field hyperfine splitting)

- $E_{HFS} = E^F(1 + \delta^{QED} + \delta^{rec} + \delta^{hvp} + \delta^{nucl})$
- Extract nuclear structure with theory model

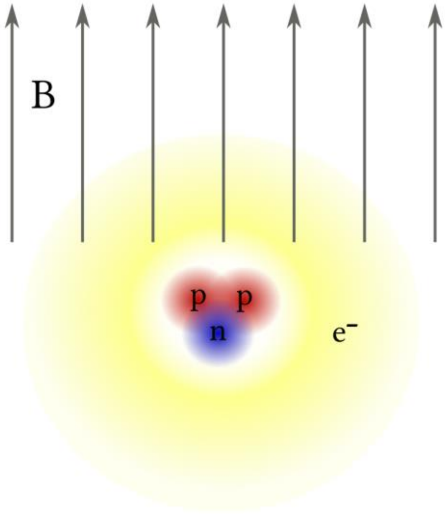
Rudzinski A., et al. *J.Chem. Phys.* **130** 244102 (2009)
Nikiel A., *et al.* Eur. Phys. J. D **68** 330 (2014)
Farooq M., *et al.* Phys. Rev. Lett. **124** 223001 (2020)

Hyperfine structure of $^3He^+$

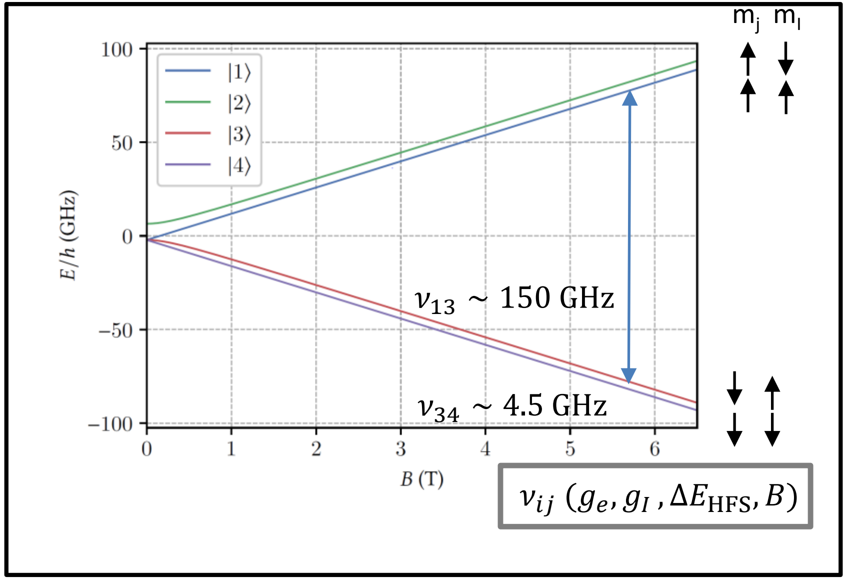
$-9 \cdot 10^{-24}$ J/T

$-1 \cdot 10^{-26}$ J/T

$$H = -\frac{1}{4}\Delta E_{\mathrm{HFS}}(\boldsymbol{\sigma}^e \cdot \boldsymbol{\sigma}^I) - (\mu_e \boldsymbol{\sigma}^e + \mu_I \boldsymbol{\sigma}^I) \cdot \boldsymbol{B}$$



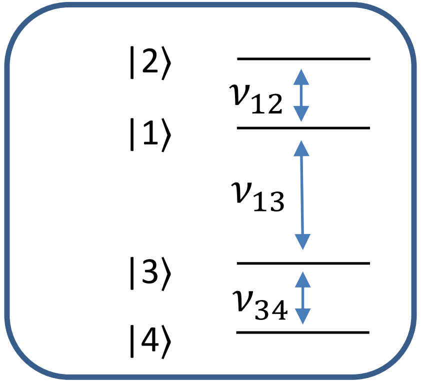
$^3He^+$ in the electronic ground state



Breit-Rabi diagram of $^3He^+$

g-factor/HFS measurement

Excitation of spin transition



$$\nu_{ij}\ (g_e, g_I\,, \Delta E_{\mathrm{HFS}}, B)$$

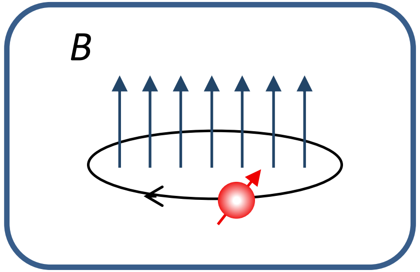
$^{3}He^{+}$

$$g_e \sim \frac{1}{B}\frac{m_e}{e} f(\nu_{12}, \nu_{13}, \nu_{34})$$

$$g_I \sim \frac{1}{B}\frac{m_p}{e} f(\nu_{12}, \nu_{13}, \nu_{34})$$

$$\Delta E_{HFS} = h(\nu_{12} + \nu_{34})$$

Simultaneous cyclotron frequency measurement



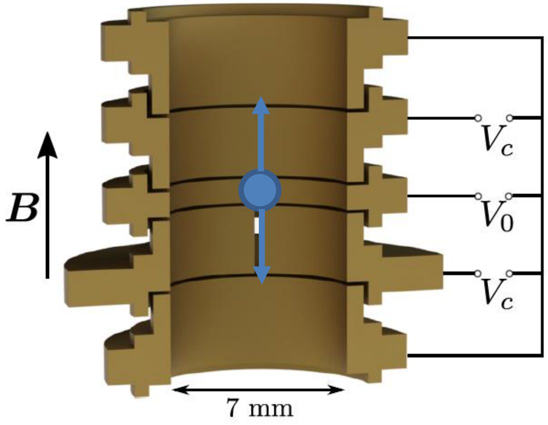
$$\nu_c = \frac{1}{2\pi}\frac{e}{m_{\mathrm{He}}} B$$

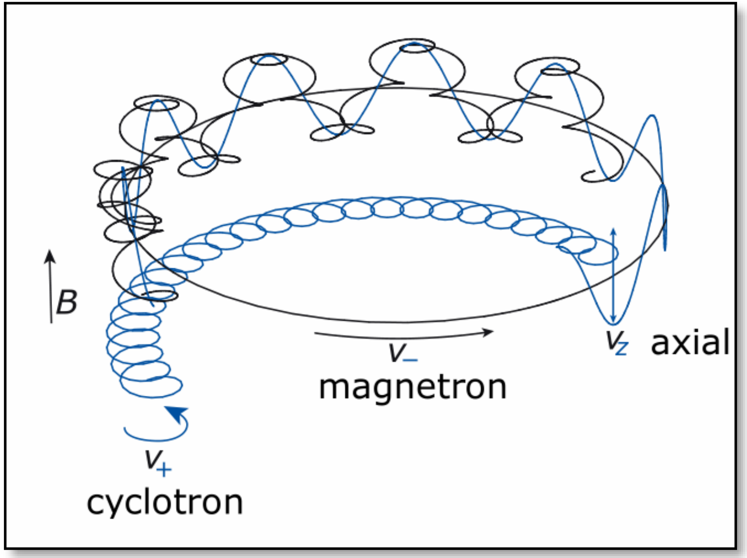
B-field independent measurement of g_e*,* g_I *and* ΔE_{HFS}

Penning trap measurements with single ions

Radial confinement: $\boldsymbol{B} = B_0 \boldsymbol{e}_z$

Axial confinement: $\Phi(\rho, z) = V_0 C_2 (z^2 - \frac{\rho^2}{2})$





$$\nu_z = \sqrt{2C_2V_0q/m}$$

$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2} = \frac{1}{2\pi}\frac{q}{m}B$$

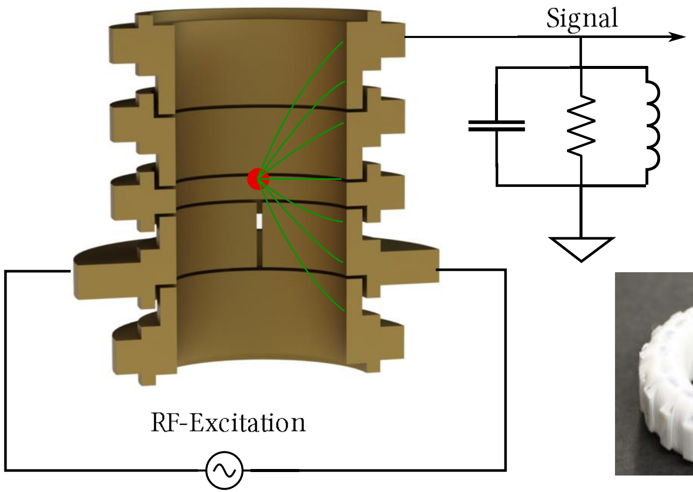
Typical values:

$\nu_+ = 30$ MHz

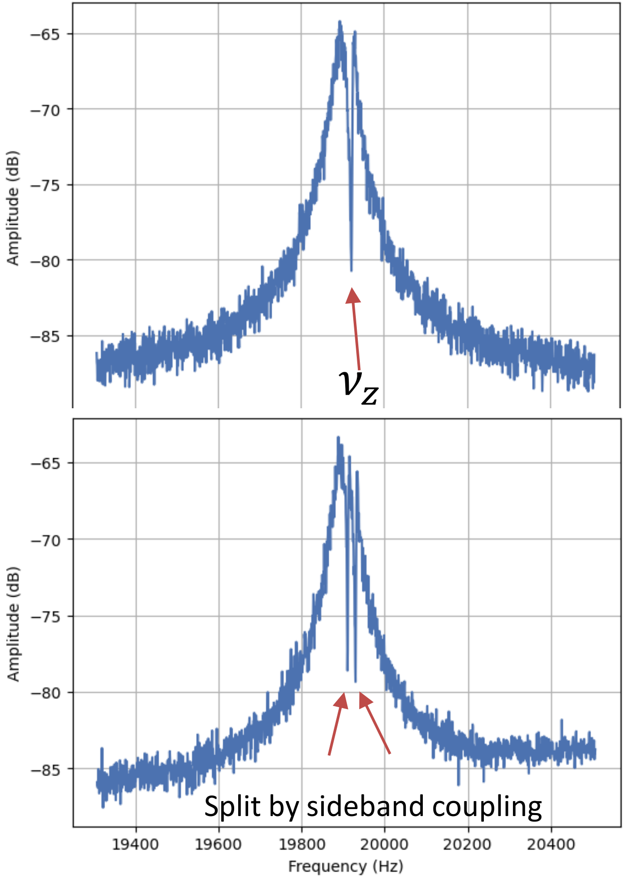
$\nu_- = 5$ kHz

$\nu_z = 500$ kHz

Penning trap frequency detection



- Thermal noise spectrum of RLC circuit is measured
- By tuning the ion's ν_z to the resonance of the RLC circuit it thermalises to 4K



Thermalised ion

Ion thermalised with sideband drive at

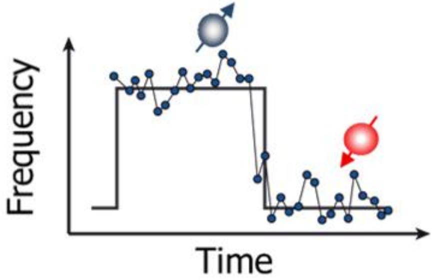
$$\nu_{\mathrm{rf}} = \nu_p - \nu_z$$

Penning trap spin-state detection

Addition of magnetic bottle inside separate analysis trap:

$$B_z = B_0 + B_2 z^2 \rightarrow \Delta\Phi(z) = -2\frac{B_2}{m}\mu_i z^2$$

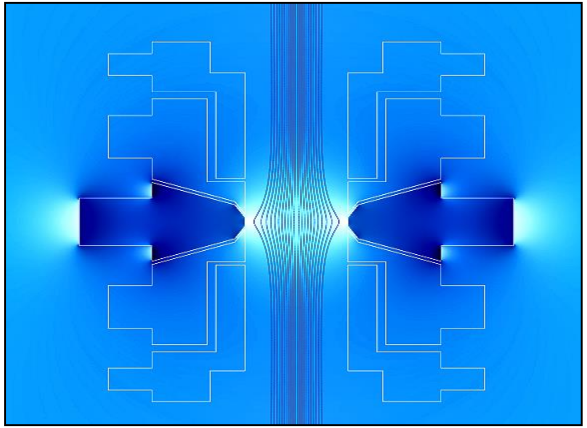
➡ Spin-state i dependent axial frequency



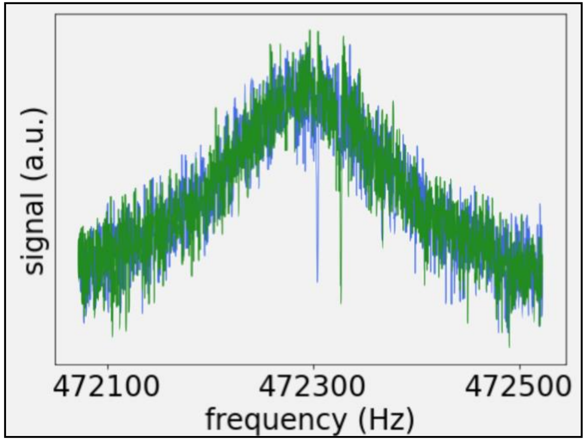
$^3He^+$:

$\Delta\nu_{z,e} \approx 22\text{Hz}$

$\Delta\nu_{z,I} \approx 100\text{mHz} \ll \nu_z$ fluctuations



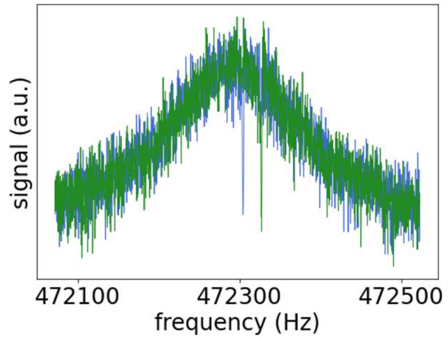
Nickel ring electrode

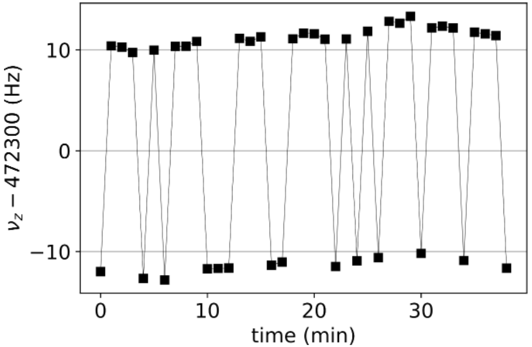


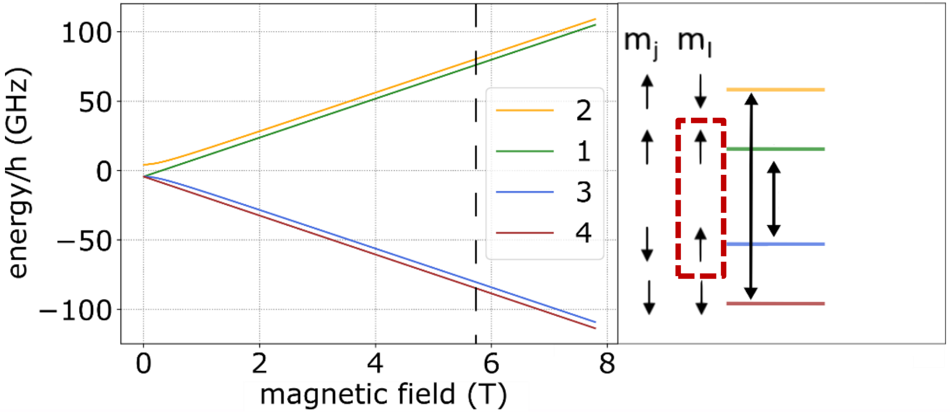
Signal for different spin states

Spin-State detection $^3He^+$

electronic spin-flip $\Delta\nu_{z,SF}$ = $20Hz$, easily detectable compared to nuclear spin-flip 100 mHz



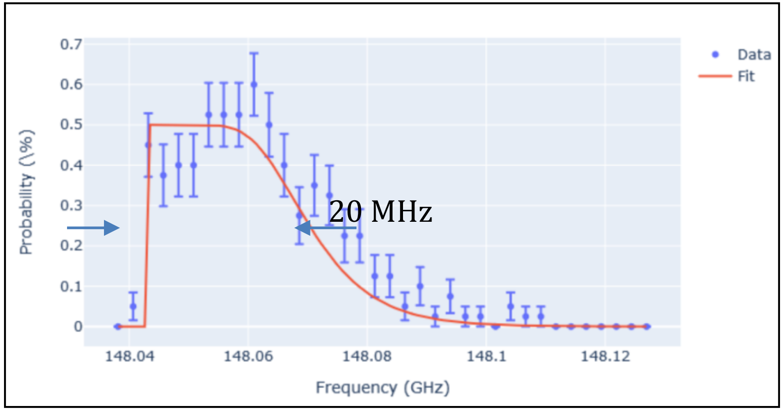


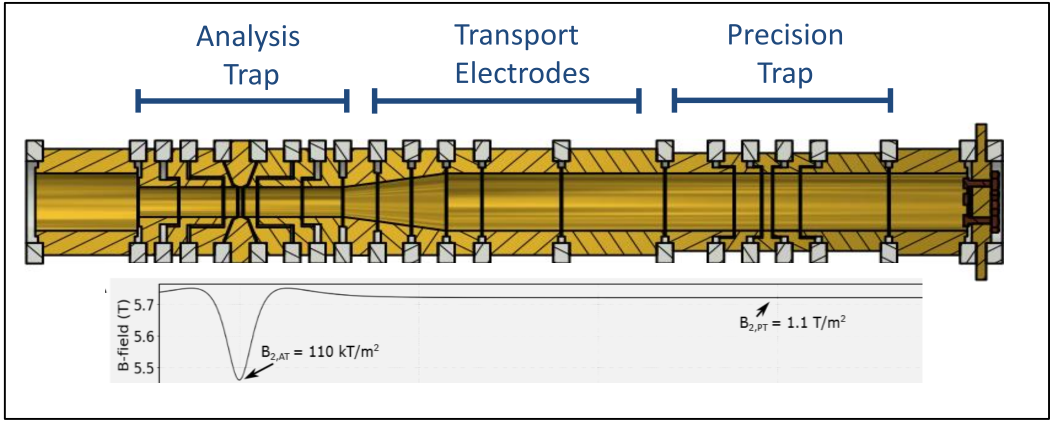


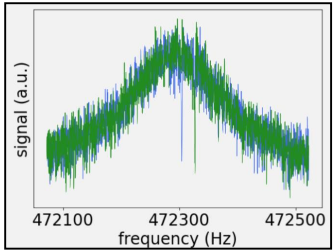
Map readout of nuclear spin-state onto detection of electron spin transitions

The double-trap technique

B_2 leads to broadened resonance

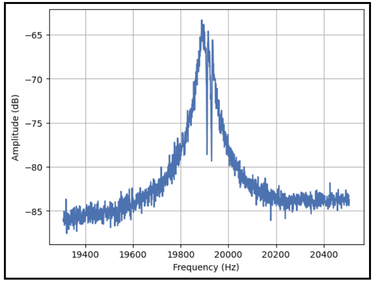






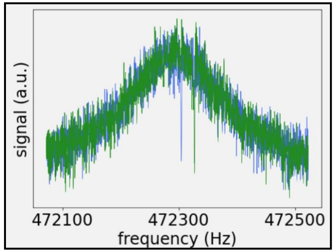
2. Transport

to the PT



4. Transport

to the AT

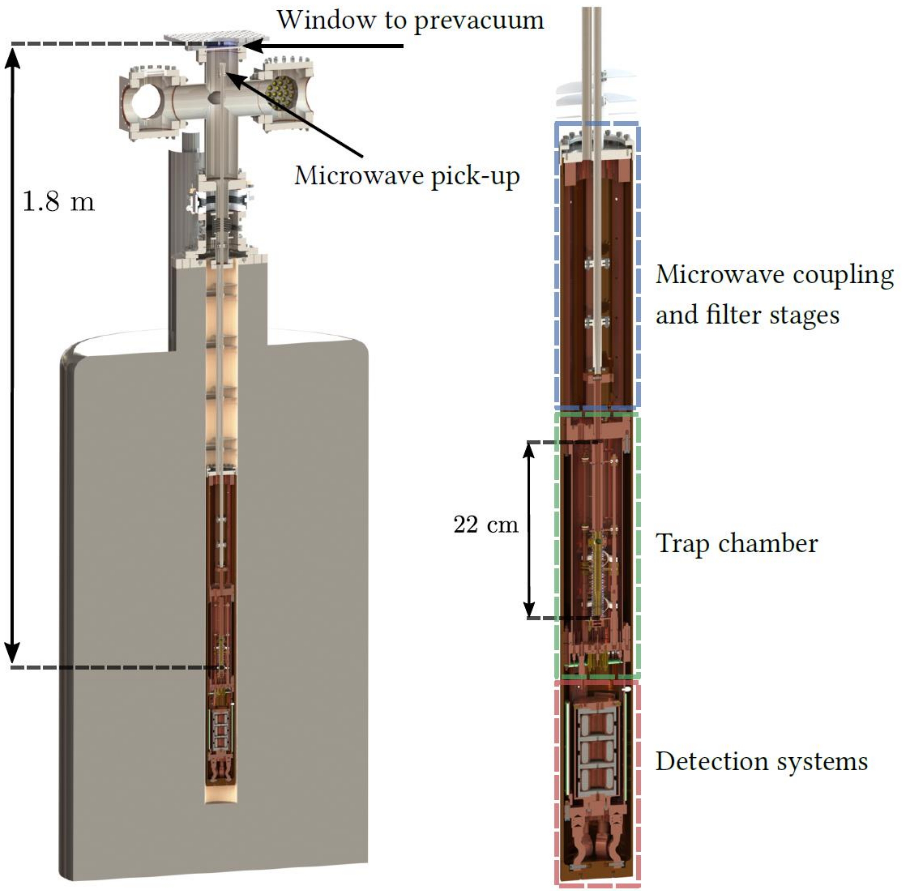


1. Spin-state determination in AT

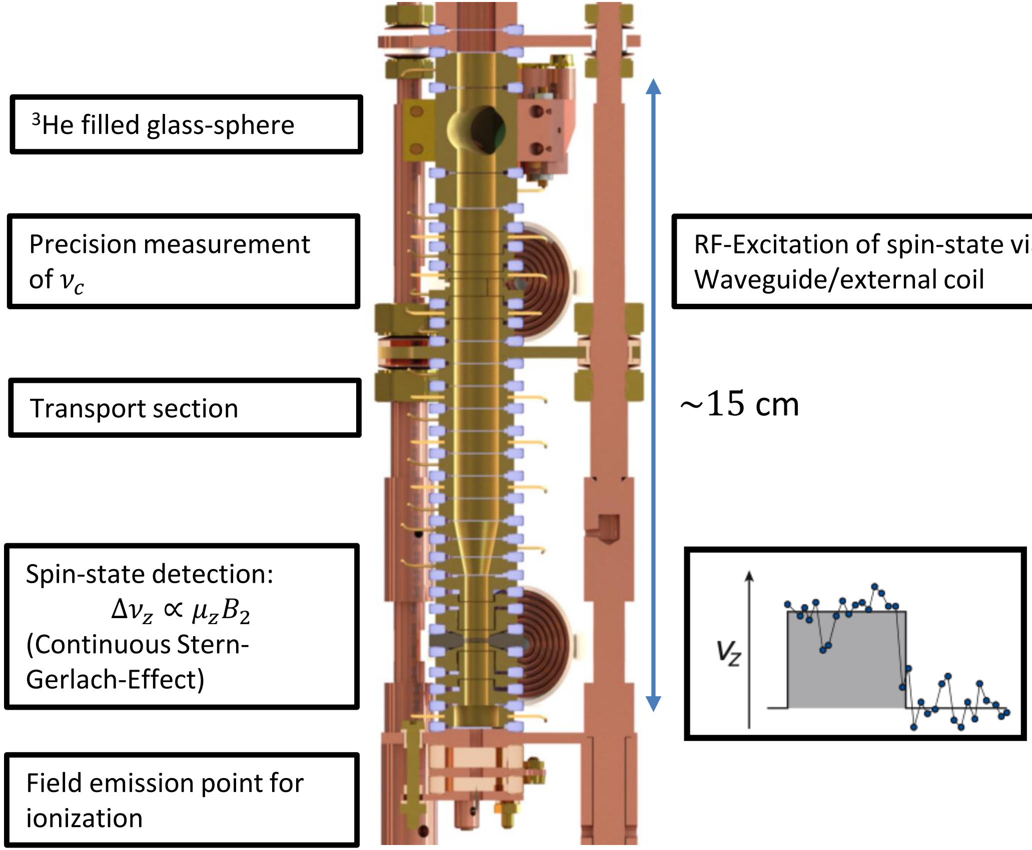
3. Cyclotron frequency measurement and simultaneous spin-flip drive in the PT

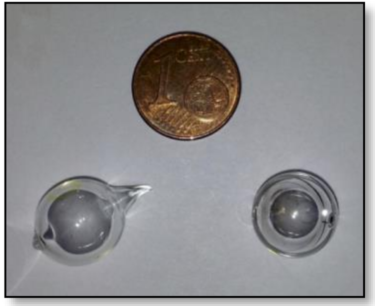
5. Spin-state determination in AT

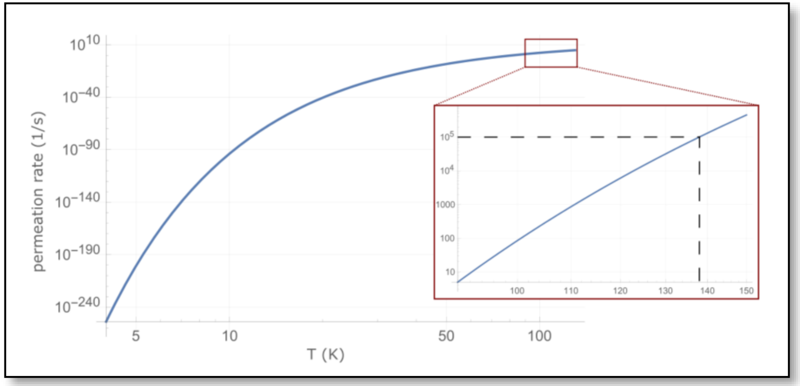
Experimental setup



The Penning-trap setup





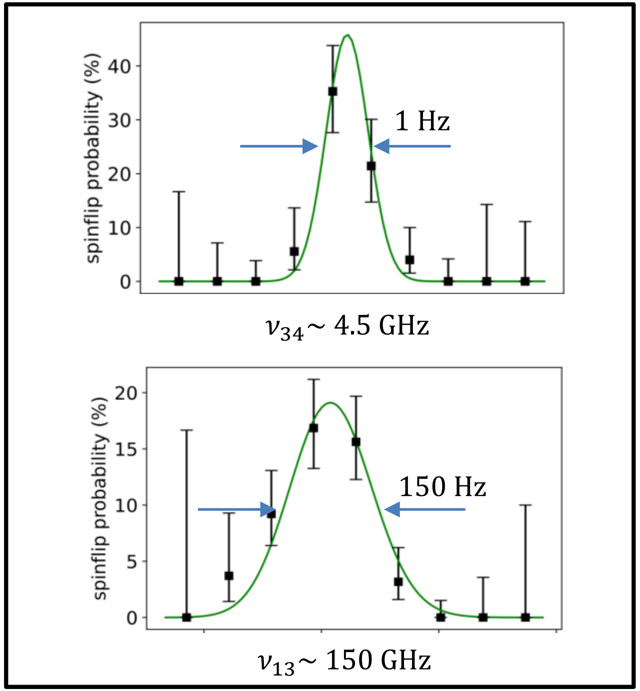


Permeation of ^{3}He through quartz-glass

- At 4K virtually no ^{3}He escapes
- Heating with a resistor produces ^{3}He atoms

Results

HFS measurement is completed



- Group of Zoltan Harman contributed theory calculations

$$\frac{\Delta g_{e,\mathrm{theo}}}{g_{e,\mathrm{theo}}} = 1.5 \cdot 10^{-13}$$

$$\frac{\Delta g_{e,\mathrm{exp}}}{g_{e,\mathrm{exp}}} = 2.5 \cdot 10^{-10}$$

$$\frac{\Delta \mathrm{E_{HFS}}}{\mathrm{E_{HFS}}} = 3 \cdot 10^{-11}$$

$$\frac{\Delta r_z}{r_z} = 7\ \%$$

$$g_I' = g_I \cdot (1 - \sigma_{\,^3\mathrm{He}^+})$$

$$\frac{\Delta(1 - \sigma_{\mathrm{theo}})}{1 - \sigma_{\mathrm{theo}}} = 3 \cdot 10^{-11}$$

$$\frac{\Delta g'_{I,\mathrm{exp}}}{g'_{I,\mathrm{exp}}} = 1 \cdot 10^{-9}$$

- $\sigma_{\mathrm{stat}} > \sigma_{\mathrm{syst}}$
- σ_{syst} dominated by B_2 dependant lineshape error in PT

Summary

Motivation

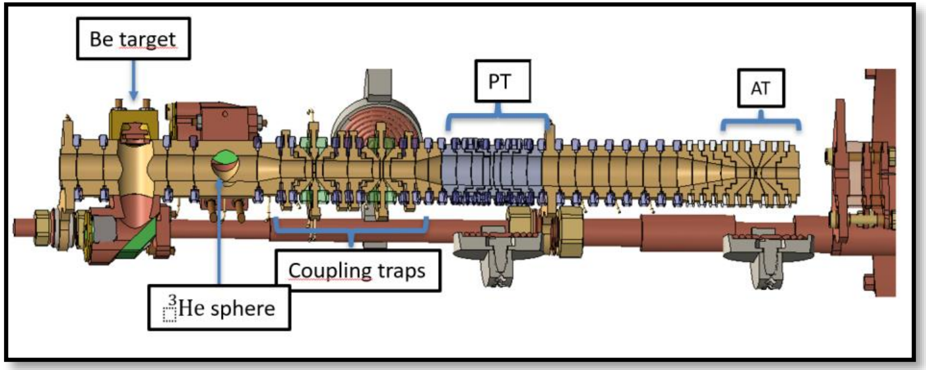
- Calibration for ^{3}He NMR probes independent of water probes
- Test of shielding parameters
- Determination of nuclear structure

HFS measurement

- Avoid direct nuclear SF detection with double-resonance technique
- Measured four HFS transitions to extract g-factors, E_{HFS} and Zemach radius

Next steps

- Direct g_I measurement of $^3He^{2+}$
- Requires sympathetic laser cooling for axial frequency stability



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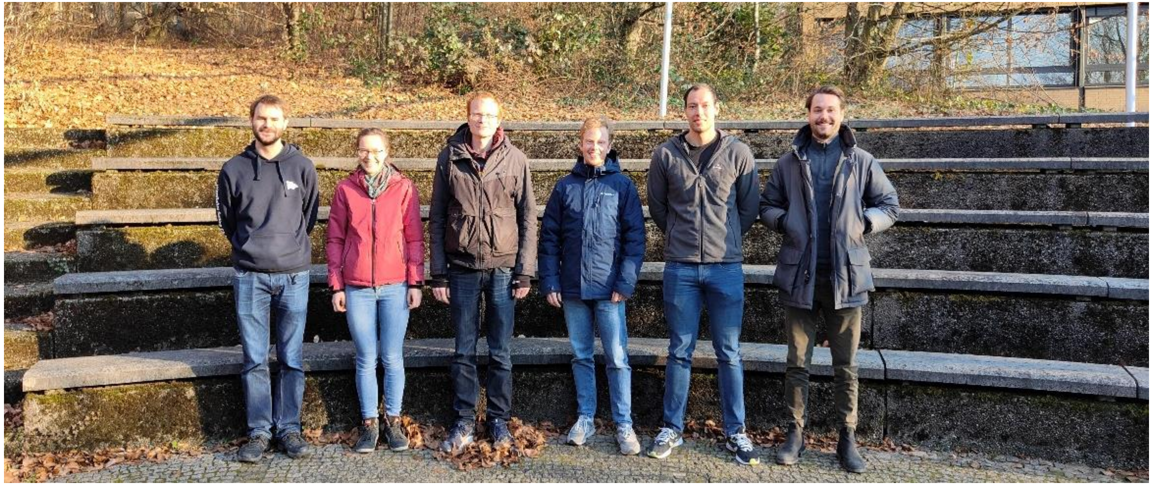

Water shielding

$$\frac{1-\sigma_{\mathrm{H_2O}}}{1-\sigma_{^3\mathrm{He}}} = \frac{\nu'_{\mathrm{H_2O}}}{\nu'_{^3\mathrm{He}}}\frac{|g_I|}{g_p}.$$

- Using the known NMR ratio $\nu'_{\mathrm{H_2O}}/\nu'_{^3\mathrm{He}}$
- Yields improved precision of water shielding $(1-\sigma_{\mathrm{H_2O}})$ of 4.5 p.p.b.