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

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Outline

1. Motivation for the HFS-measurement
2. Penning-trap measurement-principle
3. Experimental realisation
4. Results and outlook

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)

- Establish ^{3}He NMR probes for accurate magnetometry

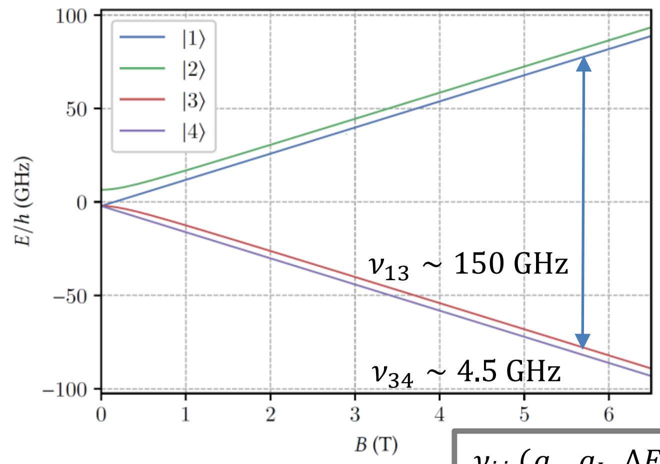
	Water NMR		^{3}He
Dependence on temperature	1	>	1/100
Dependence on probe shape	1	>	1/1000
Diamagnetic shielding	1 measured	>	1/10 calculated

- Application: muon *g*-2 experiment

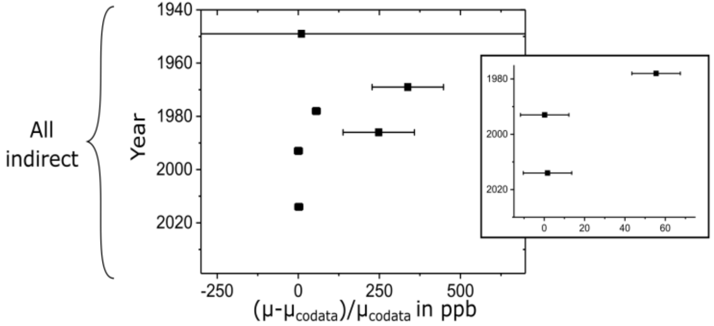
ΔE_{HFS} (zero-field hyperfine splitting)

- 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)



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



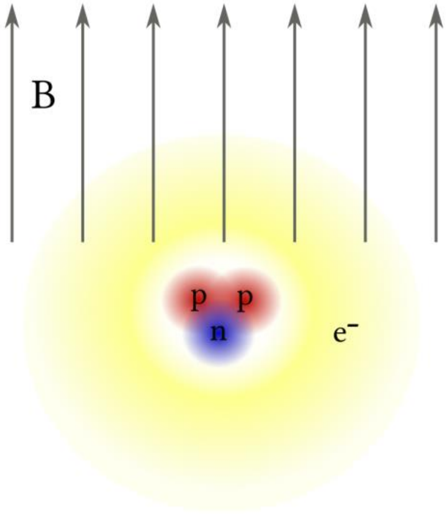
Past, indirect measurements of the nuclear magnetic moment

Hyperfine structure of $^3He^+$

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

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

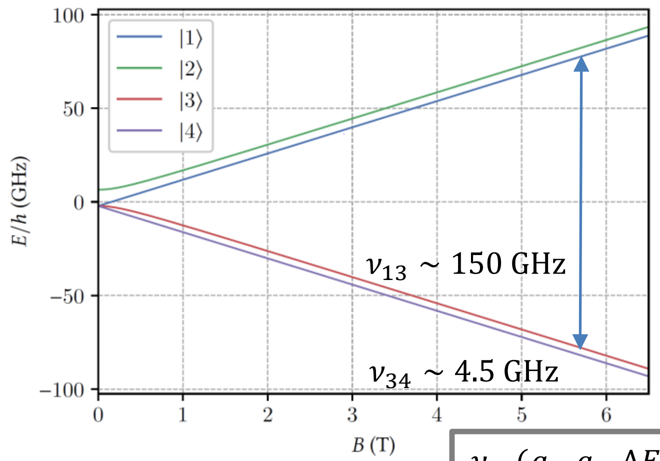
$$H = -\frac{1}{4}\Delta E_{\mathrm{HFS}}(\boldsymbol{\sigma}^e \cdot \boldsymbol{\sigma}^I) - (\mu_e \boldsymbol{\sigma}^e + \mu_I \boldsymbol{\sigma}^I) \cdot \boldsymbol{B}$$



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

Energy eigenstates of the form:

E.g. |2⟩ = a|+- ⟩ + b|-+ ⟩

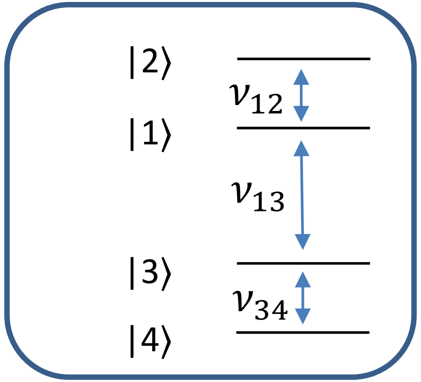


$\nu_{ij}\,(g_e, g_I, \Delta E_{\mathrm{HFS}}, B)$

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

g-factor/HFS measurement

Excitation of spin transition



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

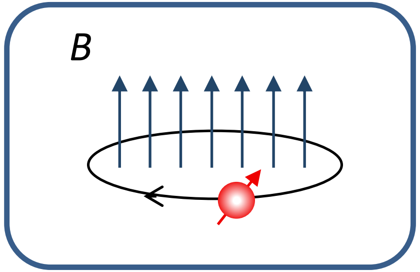
$^3He^+$

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

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

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

Simultaneous cyclotron frequency measurement



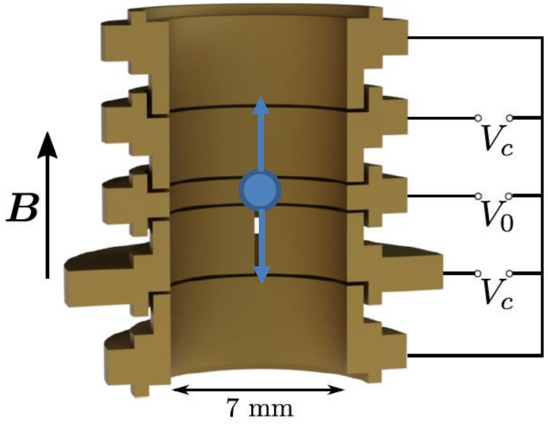
$$\nu_c = \frac{1}{2\pi}\frac{e}{m_{\mathrm{He}}} B$$

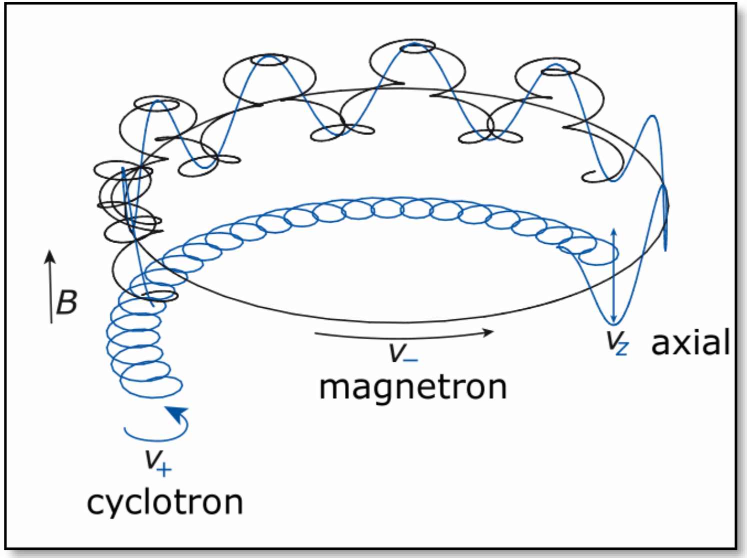
B-field independent measurement of g_e, g_I and ΔE_{HFS}

Penning trap measurements with single ions

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

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





$$\nu_z = \sqrt{2 C_2 V_0 q / m}$$

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

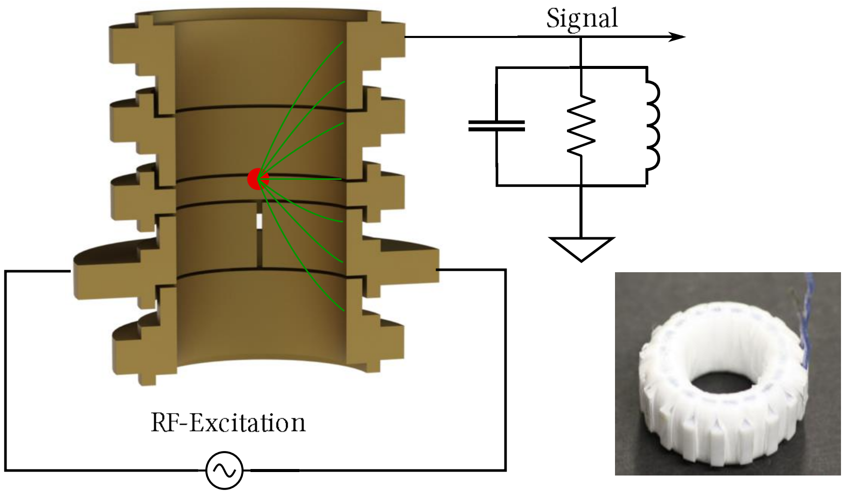
Typical values:

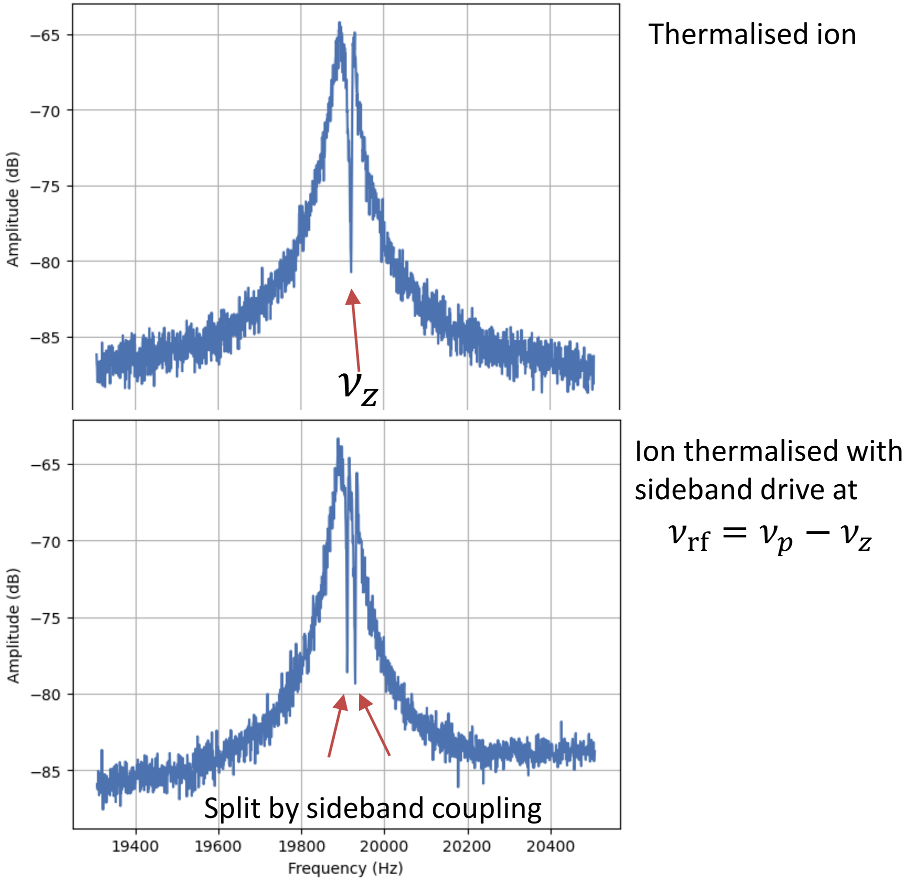
$\nu_+ = 30$ MHz

$\nu_- = 5$ kHz

$\nu_z = 500$ kHz

Penning trap frequency detection





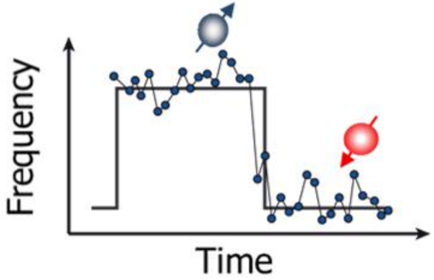
- Thermal noise spectrum of RLC circuit is measured
- By tuning the ion's ν_z to the resonance of the RLC circuit it thermalises to 4K

Penning trap spin-state detection

Addition of magnetic bottle inside separate analysis trap:

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

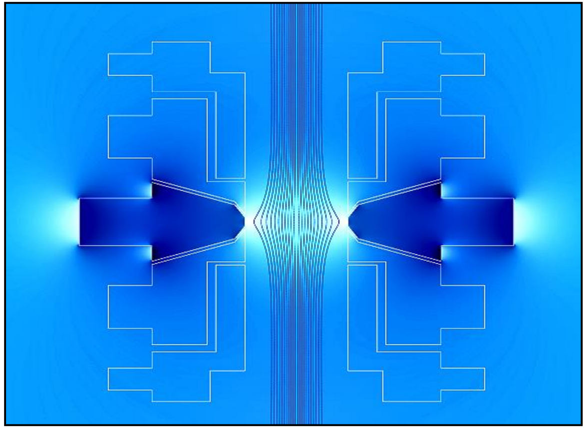
➡ Spin-state i dependent axial frequency



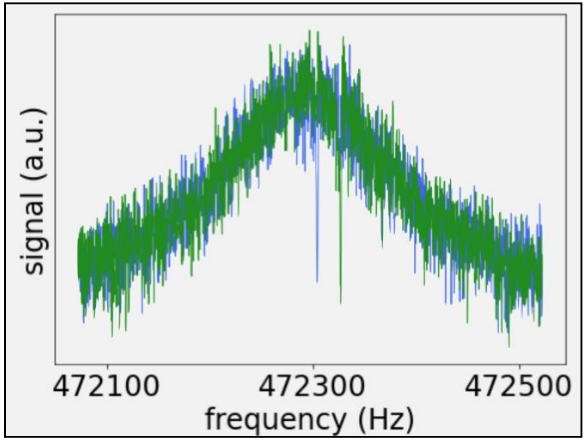
$^3He^+$:

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

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



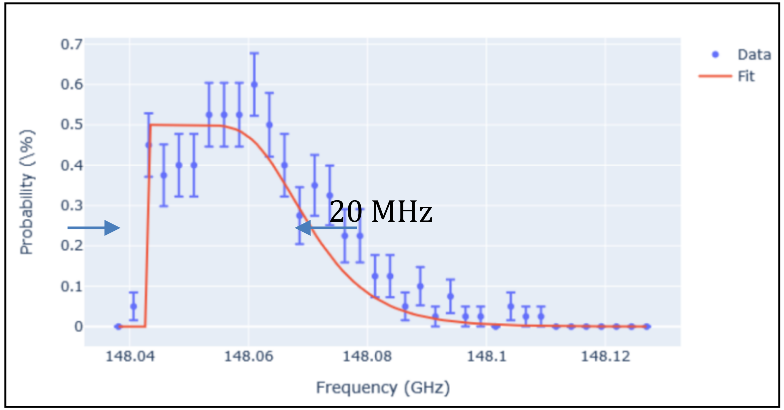
Nickel ring electrode

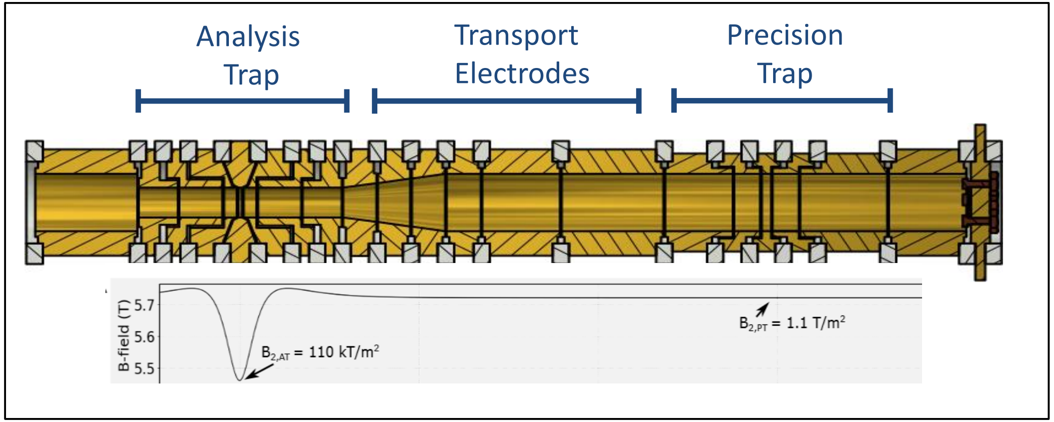


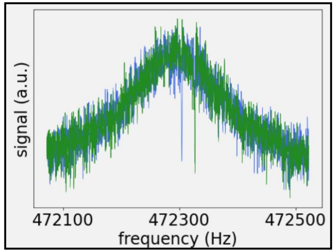
Signal for different spin states

The double-trap technique

B_2 leads to broadened resonance



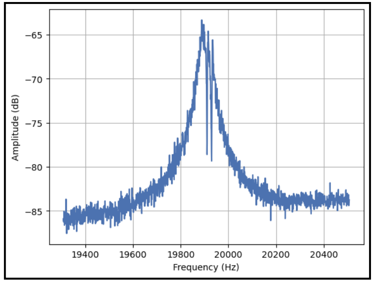




1. Spin-state determination in AT

2. Transport

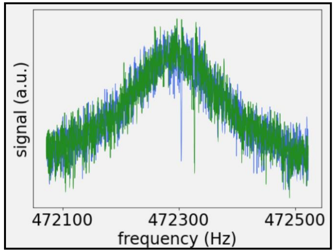
to the PT



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

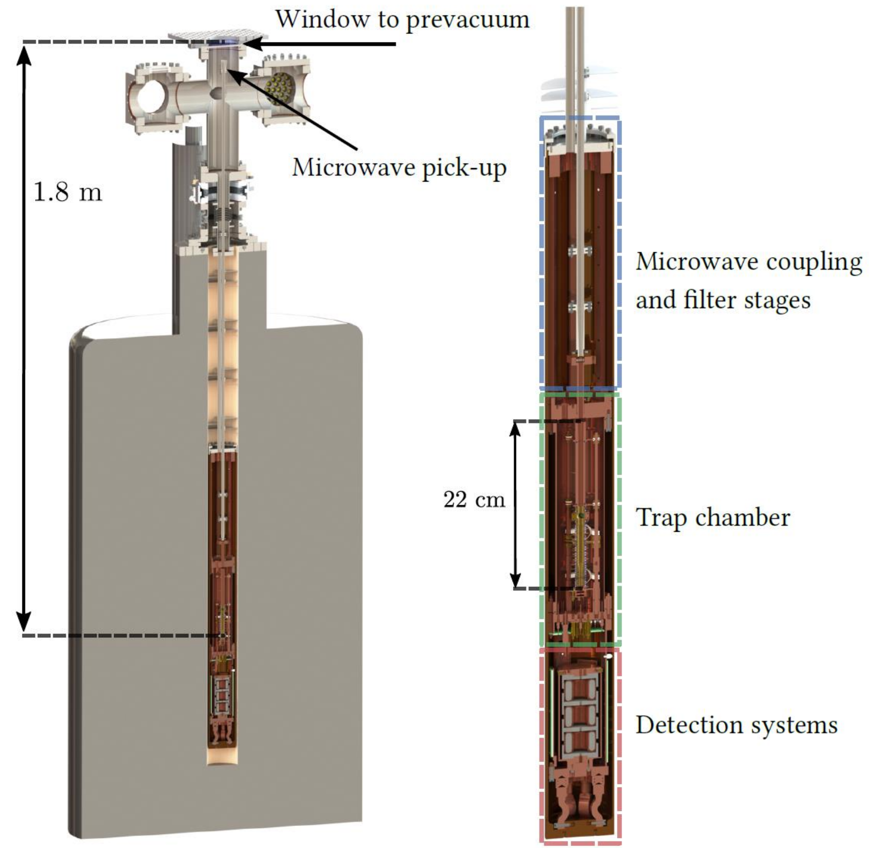
4. Transport

to the AT



5. Spin-state determination in AT

Experimental setup



The Penning-trap setup

^{3}He filled glass-sphere

Precision measurement of ν_c

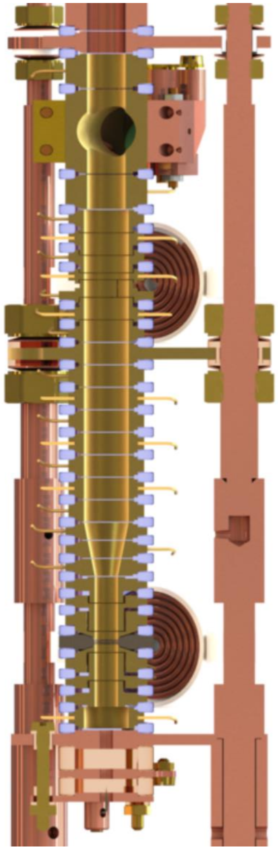
Transport section

Spin-state detection:

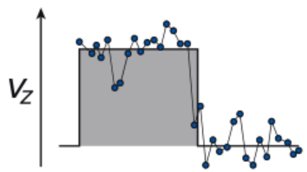
$$\Delta\nu_z \propto \mu_z B_2$$

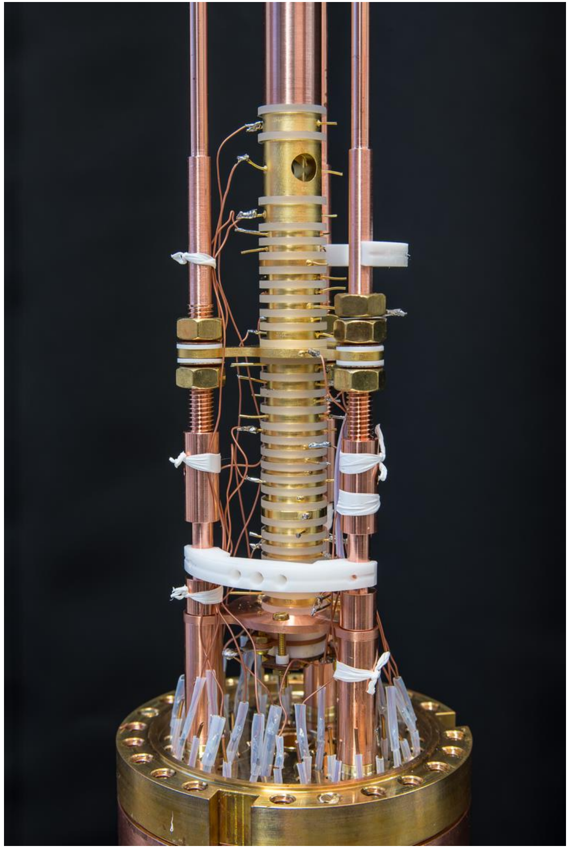
(Continuous Stern-Gerlach-Effect)

Field emission point for ionization



RF-Excitation of spin-state via Waveguide/external coil





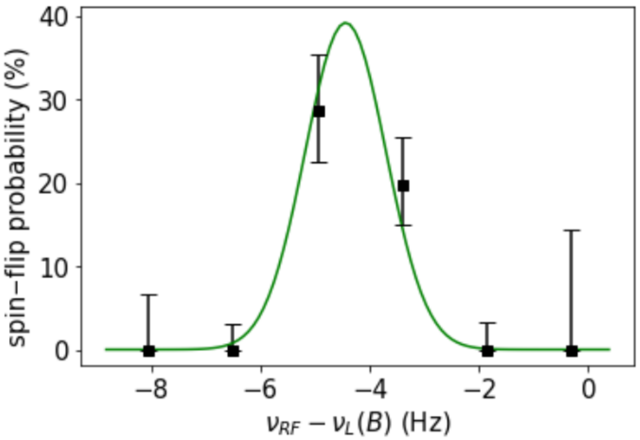
Hyperfine structure measurement data analysis

What was measured?

- Each cycle: $\mathrm{Data}_i = \{\nu_c, \mathrm{Flip}\}$

Maximum likelihood estimation

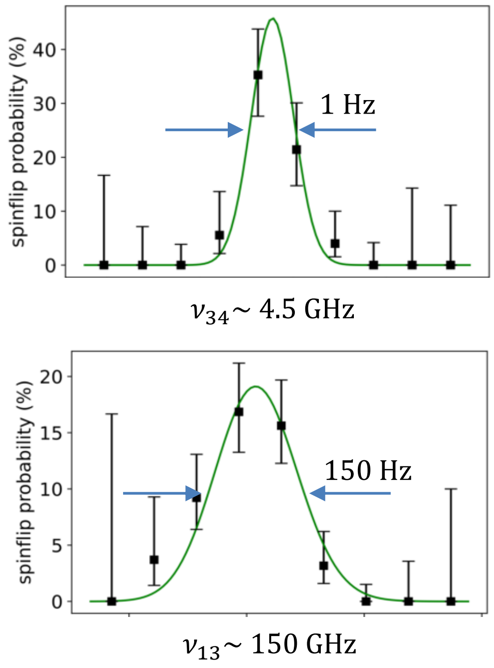
$$\mathcal{L}(g_e, g_I, \mathrm{E}_{\mathrm{HFS}} | \{\mathrm{Data}_i\}) = P_0 \cdot P_1 \cdot \cdots \cdot P_n$$



- $P_i = P(\mu_e, \mu_I, \mathrm{E}_{\mathrm{HFS}} | \mathrm{Data}_i) = P_{\mathrm{SF}}(\Delta_\mathrm{i})^{\mathrm{Flip}_i} \cdot \left(1 - P_{\mathrm{SF}}(\Delta_\mathrm{i})\right)^{1-\mathrm{Flip}_i}$
- $\Delta_i = \nu_{\mathrm{RF},i} - \nu_{L,i}(g_e, g_I, \mathrm{E}_{\mathrm{HFS}}, \nu_{c,i})$
- P_{SF} depends on T_{ion} and $B_{2,\mathrm{PT}}$ → limits our precision of g_e and g_I

Results

HFS measurement is completed



- Group of Zoltan Harman contributed theory calculations

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

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

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

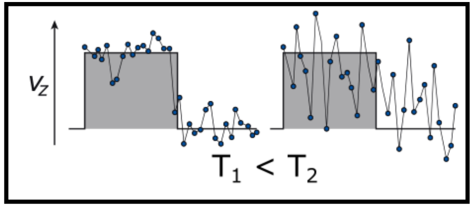
$$\frac{\Delta(1 - \sigma_{\mathrm{theo}})}{1 - \sigma_{\mathrm{theo}}} = 3 \cdot 10^{-11}$$

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

Current status

Measurement of the g-factor of $^3He^{2+}$ (not shielded!)

- Requires much lower temperature of the ion



- Introduce sympathetic cooling to laser cooled Be^+ ions
- Addition of coupling traps