A New Experiment to measure the g-Factors of ${}^{3}\mathrm{He}^{+}$ and ${}^{3}\mathrm{He}^{2+}$

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Motivation

First direct high-precision measurement of $^{3}He^{2+}$ nuclear magnetic moment with ppb or better

- Establish hyper-polarized ^{3}He NMR probes as independent standard for precision magnetometry
- $\Delta B/B = 10^{-12}$ in seconds using hyperpolarized ^{3}He

	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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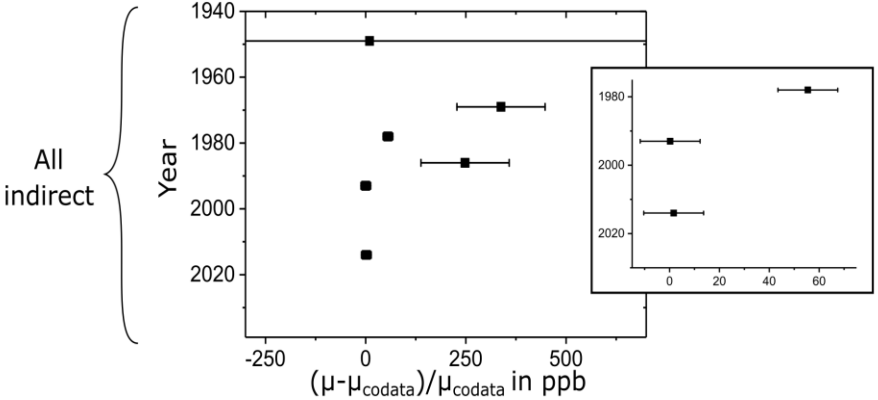

However

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

limited by knowledge of shielded proton magnetic moment

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Test of diamagnetic shielding parameter

- Ratio of NMR frequencies (known to 3ppb)

$$\boxed{\frac{\omega_{He}}{\omega_{H2}} = \frac{\mu_{He}(1-\sigma_{He})}{\mu_p(1-\sigma_{H2})}}$$

➡ ppb measurement of μ_{He} will allow for test of theoretical shielding parameter ratio with ppb precision

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- Discrepancies between σ_H obtained from comparison to ^{3}He or H_2

  Can be explained by:
  - 100ppb shift of μ_{He}
  - Inconsistencies in diamagnetic shielding scales for protons

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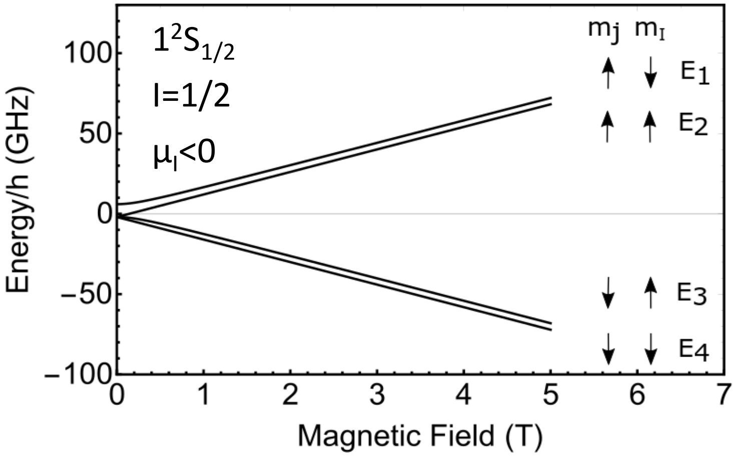
Hyperfine splitting of $^3He^+$



- Determination of:
  - Zero-field ground-state hyperfine splitting ΔE^{HFS}
  - Nuclear and electronic *g*-factor
- ΔE^{HFS} known to 1.1 ppb (Schuessler et al., Phys. Rev. **187** 5 (1968))

We aim for measurement of order 100ppt

A. Mooser *et al.*, J. Phys. Conf. Ser. **1138**, 012004 (2018)

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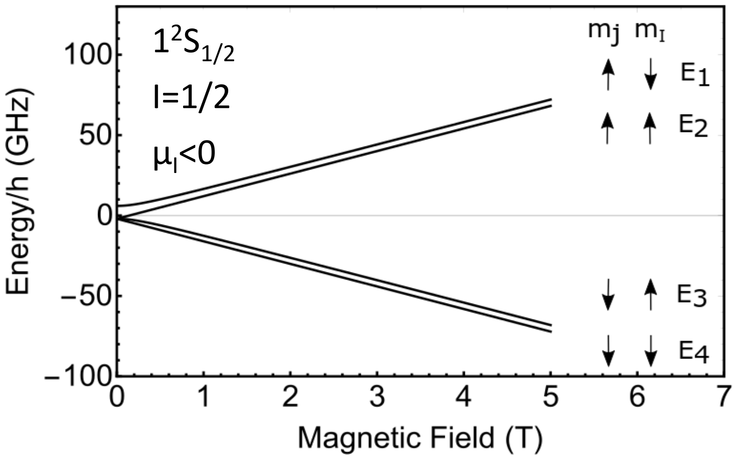

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$$\Delta E^{HFS} = E^F(1 + \delta^{QED} + \delta^{rec} + \delta^{hvp} + \delta^{nucl})$$ with Fermi contact energy E^F

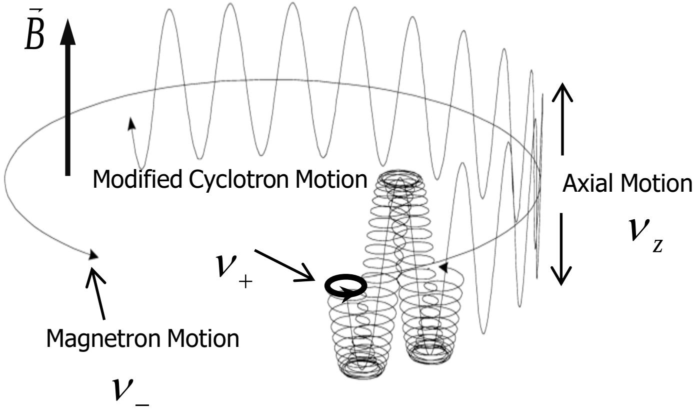
⇨ determination of e.g. nuclear structure effect δ^{nucl}

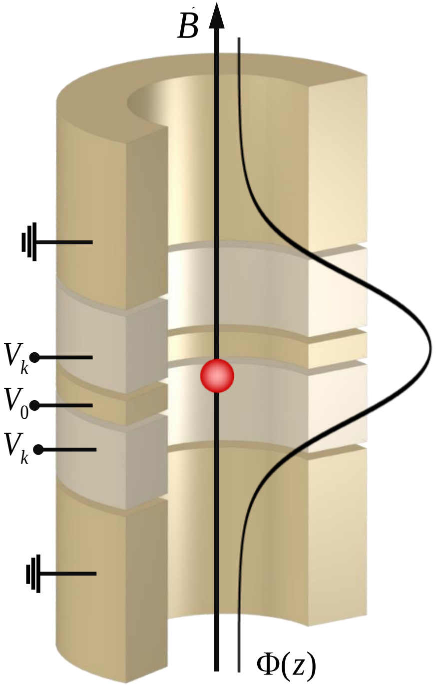
A. Mooser *et al.*, J. Phys. Conf. Ser. **1138**, 012004 (2018)

Main Tool: Penning Trap

radial confinement: $B = B_0\hat{z}$

axial confinement: $\Phi(\rho, z) = V_0 c_2\left(z^2 - \frac{\rho^2}{2}\right)$





Axial frequency	ν_z = 680 kHz
Magnetron frequency	ν_- = 5 kHz
Modified cyclotron frequency	ν_+ = 50 MHz

(example proton)

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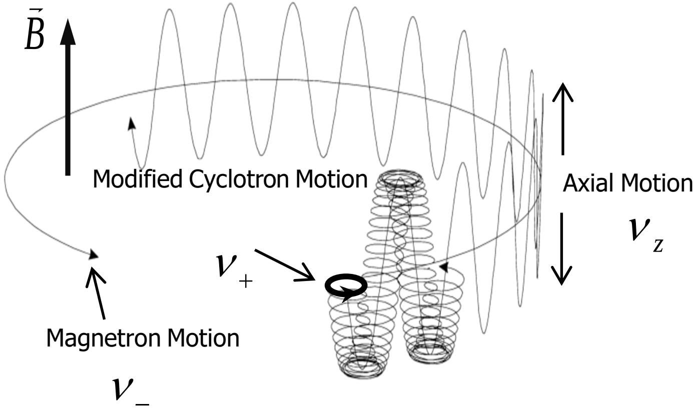

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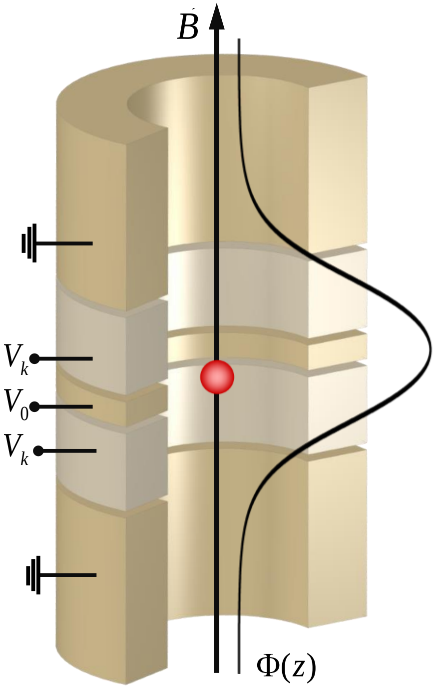


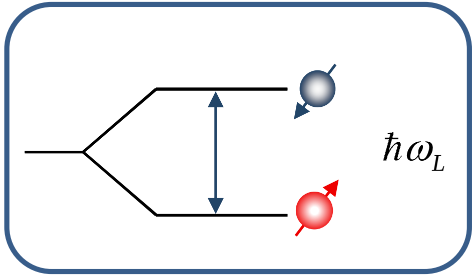
Invariance-Relation

$$\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2}$$

$$\boxed{\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B}$$

Magnetic Moments in Penning Traps

Determination of energy splitting between spin-states

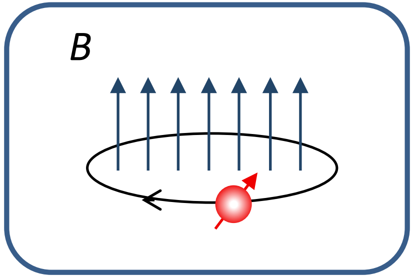


$$\omega_L = 2\frac{\mu_{He}}{\hbar}B$$

$^3He^{2+}$

$$\frac{\mu_{He}}{\frac{e\hbar}{m_{He}}} = \frac{\omega_L}{\omega_c}$$

Simultaneous cyclotron frequency measurement



$$\omega_c = \frac{2\,e}{m_{He}}B$$

To determine g-factor of ^3He – either proton-helion mass ratio needed (known to 30ppt) – or .....

Magnetic Moments in Penning Traps

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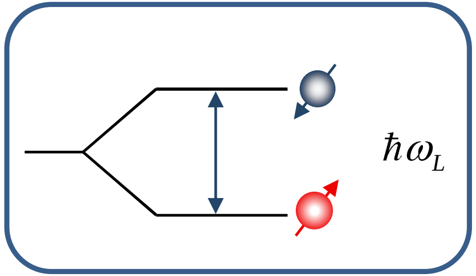
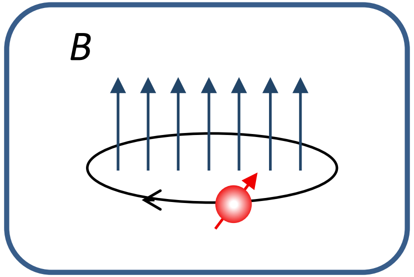


$^3He^{2+}$

Proton

Simultaneous cyclotron frequency measurement



$$\omega_L = g_{He}\frac{e}{2m_p}B$$

$$\frac{\mu_{He}}{\mu_N} = \frac{\omega_L}{\omega_c} = \frac{g_{He}}{2}$$

$$\omega_c = \frac{e}{m_p}B$$

Principle demonstrated for antiproton magnetic moment - Smorra et al. *Nature* **550**, 371 (2017)

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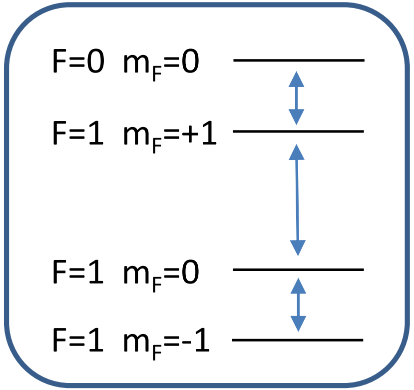


$$\omega_{F=I\pm\frac{1}{2}}\left(g_I, g_j, \Delta E^{HFS}, B\right)$$

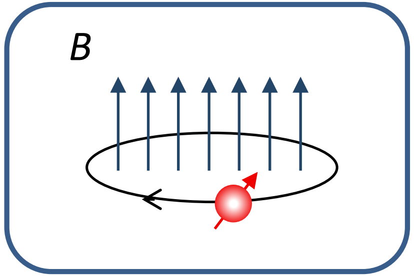
$^3He^+$

$1^2S_{1/2}$

$I=1/2$

$\mu_I<0$

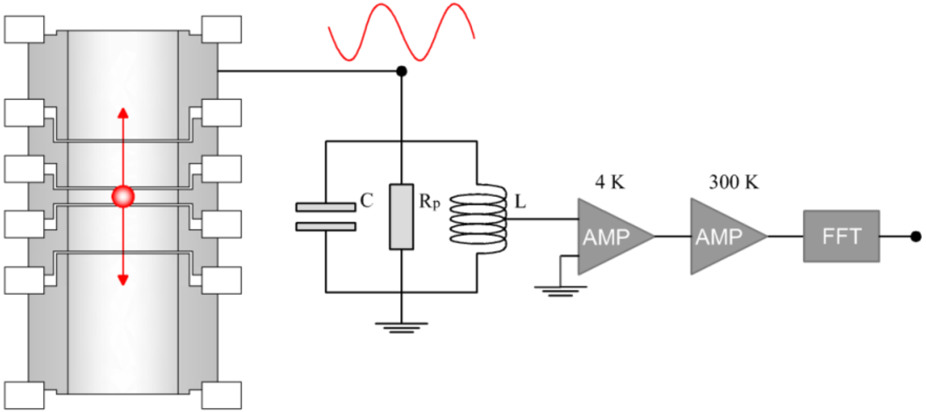
Simultaneous cyclotron frequency measurement



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

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

Image Current Detection



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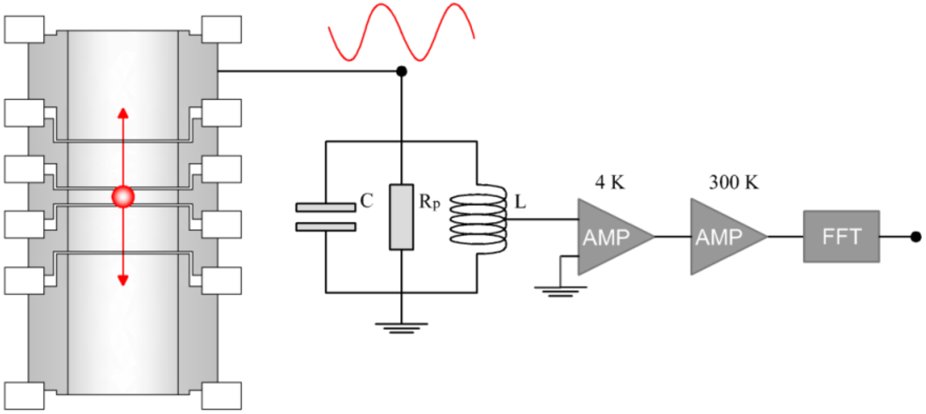
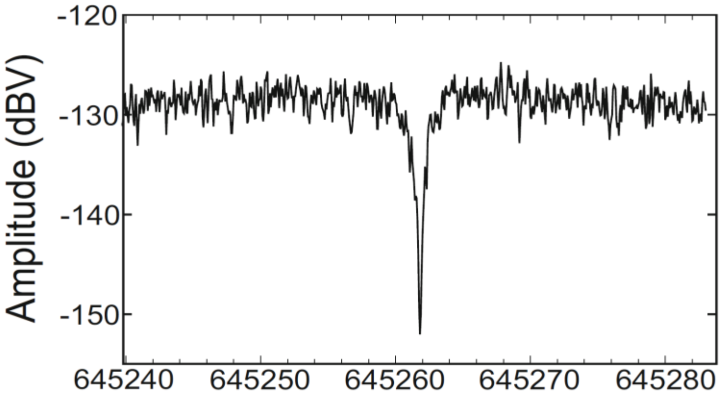


- Thermal equilibrium: dip at eigenfrequency of the ion
- The particle dissipates energy and is resistively cooled

Axial frequency dip of a single antiproton

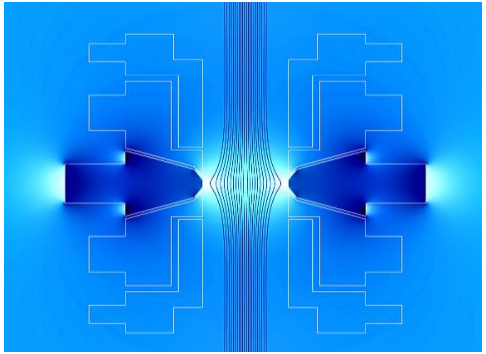


Detection of Spin-State - Continuous Stern-Gerlach Effect

Introduce magnetic field inhomogeneity

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

Ring electrode made of CoFe



Spin-transition induces frequency jump

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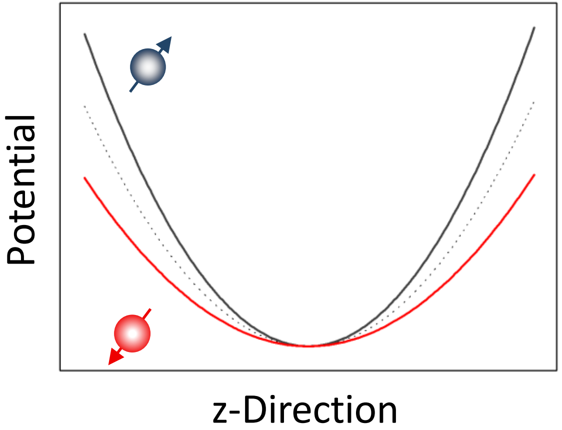
Spin-dependent motion of ion

$$\Phi_z = \pm\mu_p B_z$$



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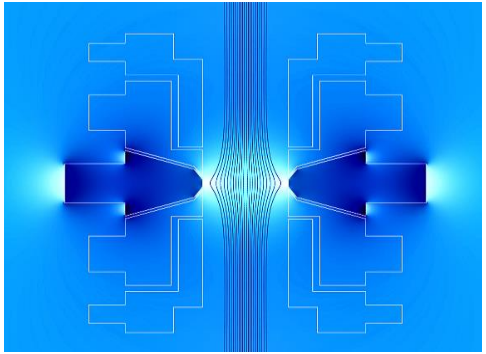

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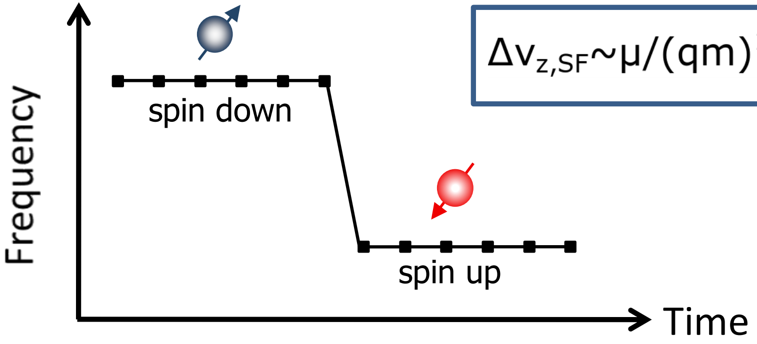

$\Delta\nu_{z,SF} \sim \mu/(qm)^{1/2}$

Spin-State Detection ^{3}He$^+$

Detect electron spin-transition using cont. Stern-Gerlach effect

⇒ $\Delta\nu_{z,SF}$ of order $10Hz$, much easier to detect compared to 90mHz

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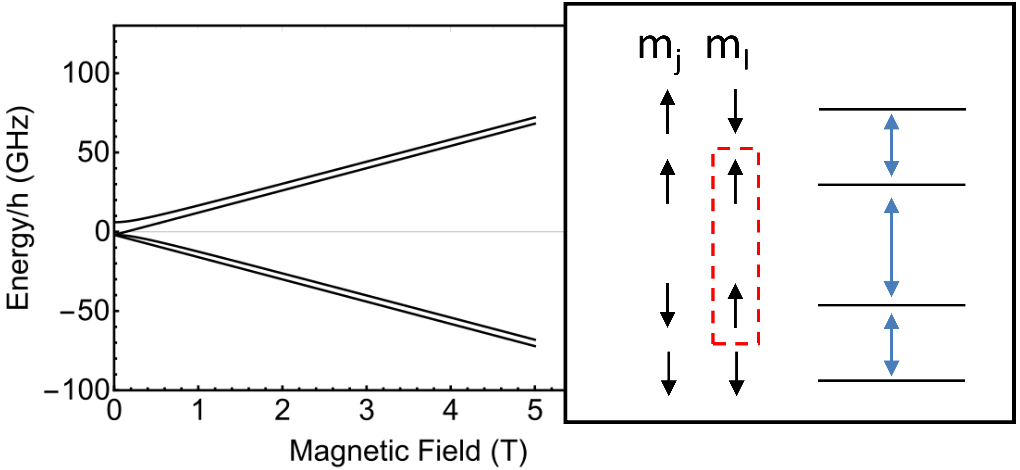
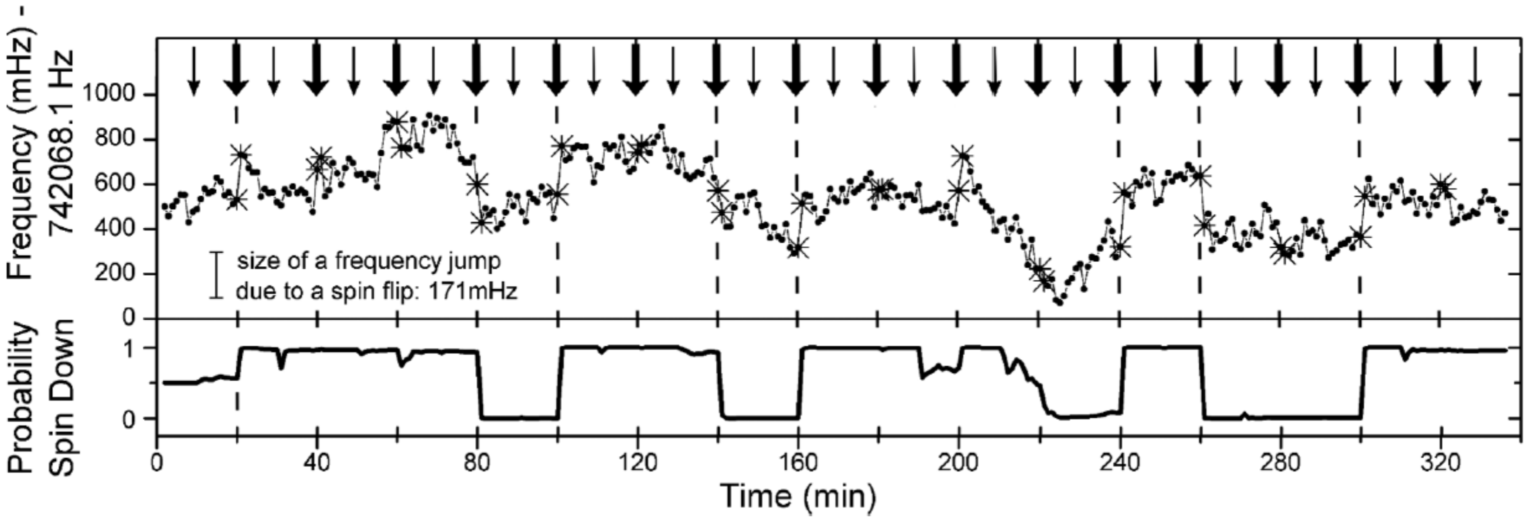


Map readout of nuclear spin-state onto detection of electronic spin-transition

Challenge of nuclear Spin-State Detection

Example measurement with proton:



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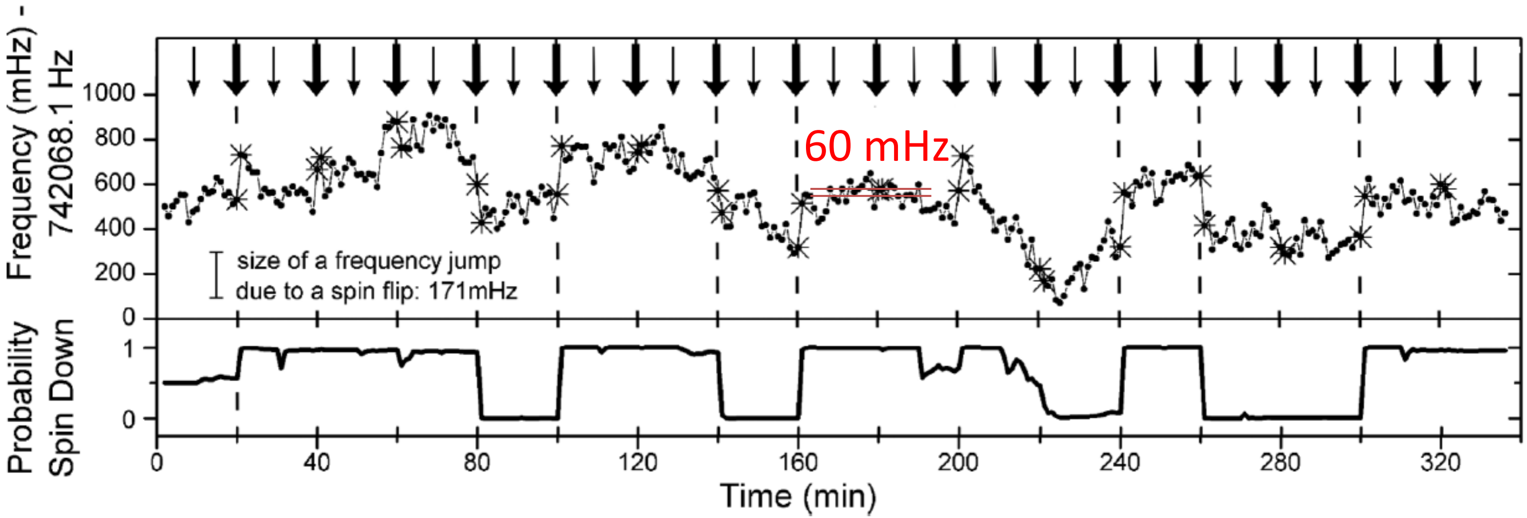

Spin-flip frequency shift reduced by factor 3 for $^3He^{2+}$ compared to proton

A. Mooser *et al.*, Phys. Rev. Lett. **110**, 140405 (2013).

Challenge of nuclear Spin-State Detection

- Magnetic bottle also couples the radial motion to the axial frequency
- Noise on electrodes of some pV/Hz$^{1/2}$

  → random cyclotron quantum transitions
- Transition rate $dn_+/dt \sim n_+$:
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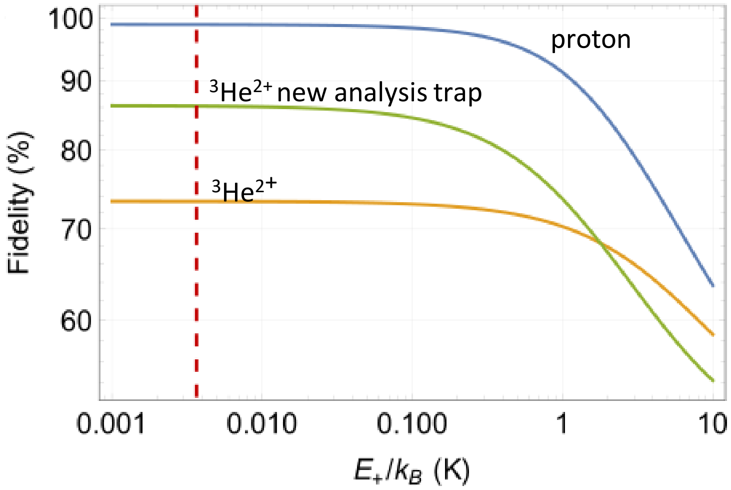

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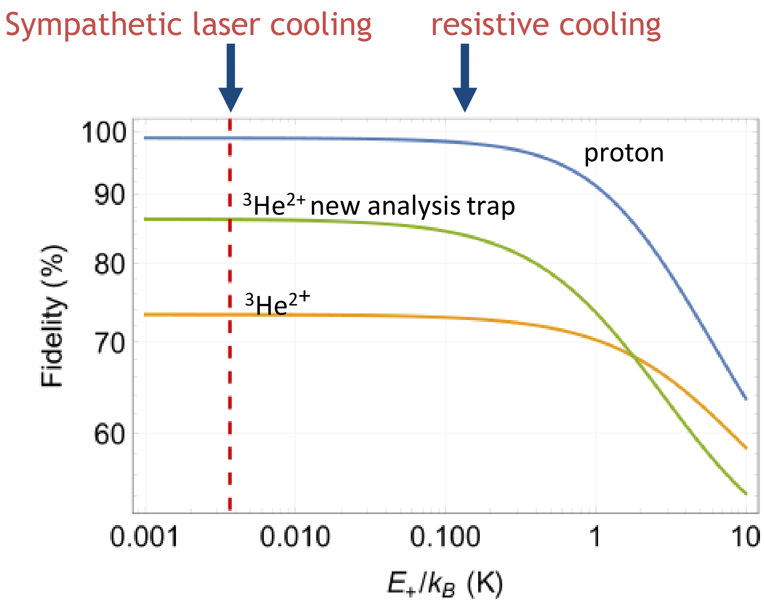

New Analysis Trap

- Small trap radius (1.25mm):
  - Inhomogeneity doubled compared to

    1.8mm radius 600 T/mm²
  - However also larger axial frequency

→ $\Delta\nu_{z,SF} \sim \frac{\mu_k B_2}{m\nu_z}$ ~90mHz compared to 60mHz

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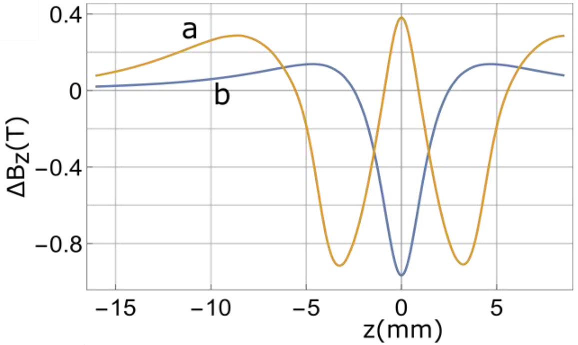
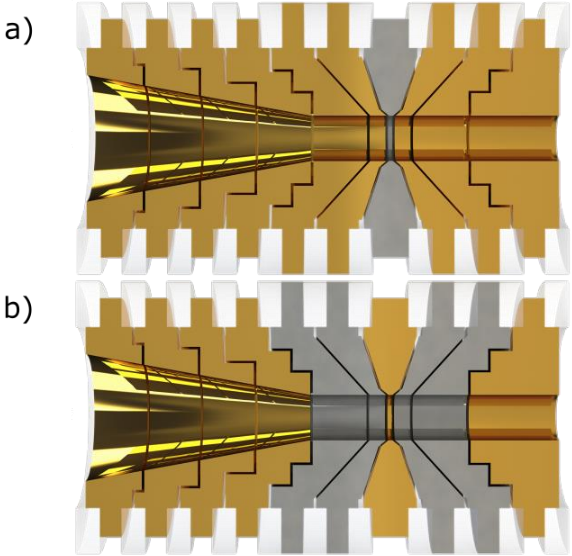
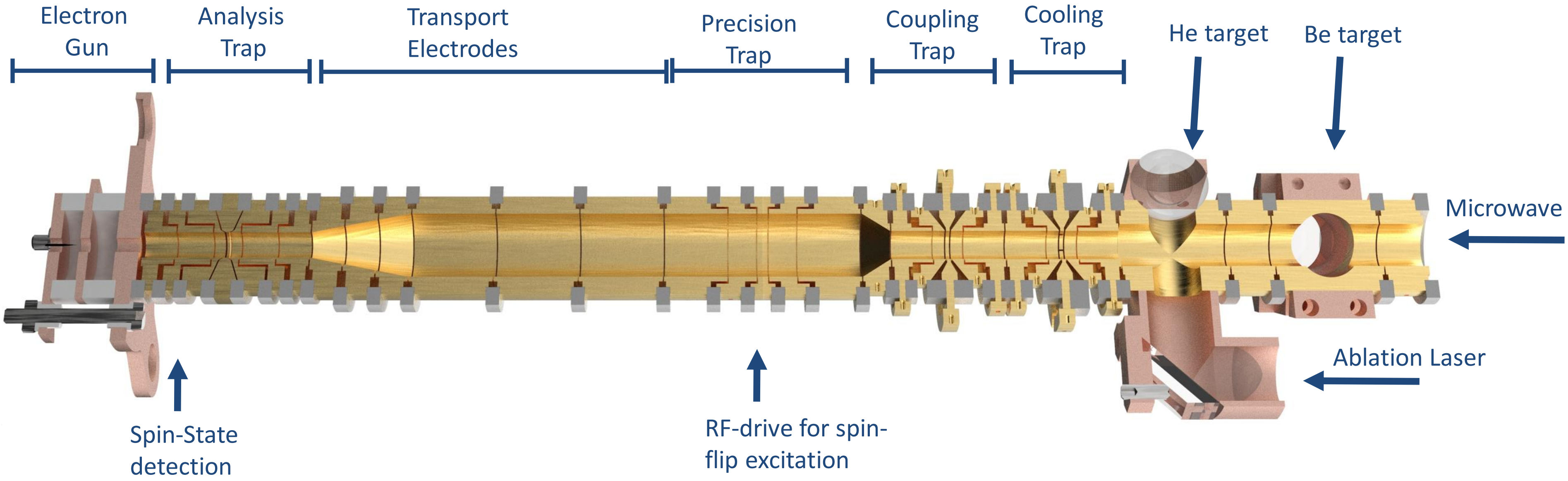
- Ferromagnetic correction electrodes:
  - Larger energy spacing between cyclotron quantum states
  - Reduces rate for random cyclotron quantum transitions





Trap Setup


Electron Gun
Analysis Trap
Transport Electrodes
Precision Trap
Coupling Trap
Cooling Trap
He target
Be target
Microwave
Ablation Laser
Spin-State detection
RF-drive for spin-flip excitation

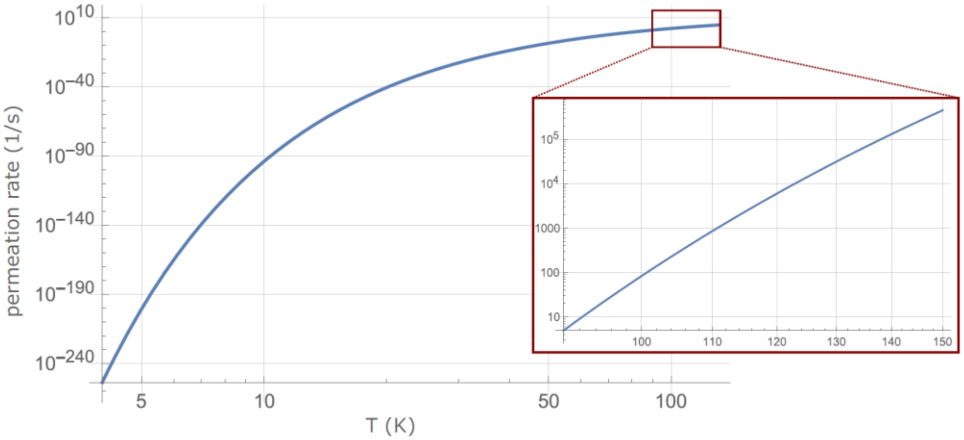
Test of internal ^{3}He source

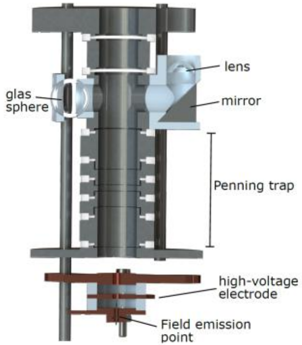
- Avoid external inlet for improved vacuum
- Possibile sources:

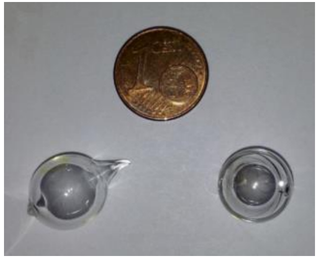
1. Tritium in TiH_2 after decay to ^{3}He
2. ^{3}He rich meteorites
3. ^{3}He filled glas sphere:

   Strongly temperature dependent helium permeation through glass

- Penning trap setup dedicated to He source test







W. Heil – University of Mainz

Summary

Nuclear magnetic moment of $^3He^{2+}$

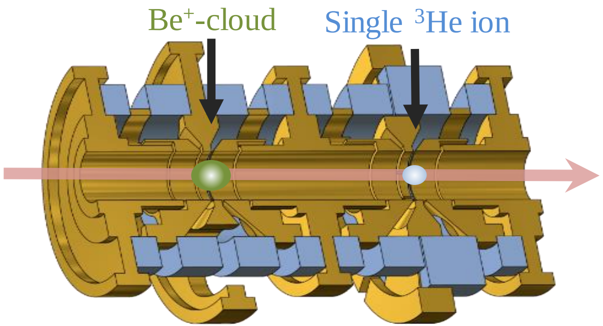
- Hyperpolarized ^3He as independent and uncorrelated B-field probe
- Uncorrelated measurement to test water probe: different and in cases smaller systematic effects
- Design of new experiment
- Due to reduced sensitivity on spin-state – new analysis trap and sympathetic laser cooling

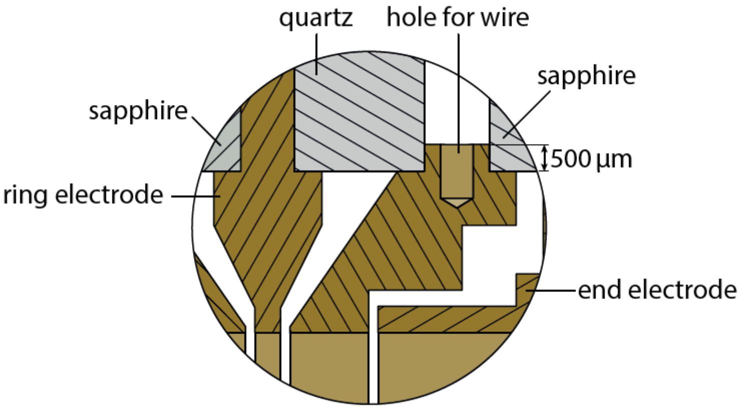
Ground-state HFS of $^3He^+$

- Novel nuclear spin-state detection scheme
- Complementary determination of e.g nuclear structure effect

Sympathetic Laser Cooling

- Plan to implement *common end cap* technique



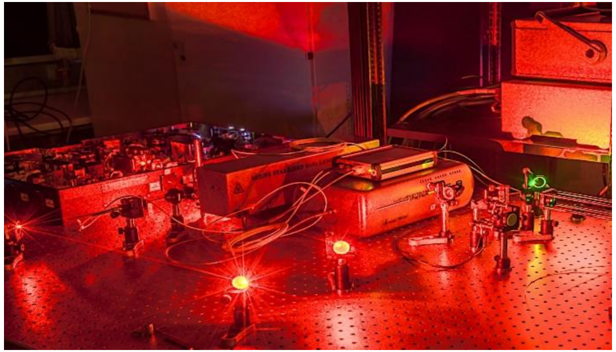


$$\tau_{exc} = 2\,\pi\,\omega\,C_T\,\frac{\sqrt{m_p m_{Be}}}{q^2}\,D_{eff}\,\frac{1}{\sqrt{N_{Be}}}$$

To optimize:

- N_{Be} - Increase number of Be ions
- D_{eff} - Reduce trap dimensions
- C_T - Reduce trap capacitance
- ω - Reduce oscillation frequency

⇒ Coupling times τ_{exc} of order 10sec



M. Bohmann *et al.*, J. Mod. Opt. **65**, 601 (2018)

Design of new Experiment

Electronics

Alignment

Pre-Vacuum / Cryogenic valve

Penning Trap

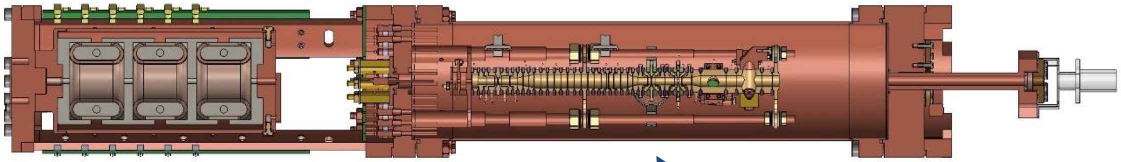
Detection

Ultra-High Vaccum Interface

- Microwave access
- Laser access
- Signal Lines

Laser ports

- 313nm fiber coupled
- 2 x ablation laser free running



Detection Systems

- Superconducting toroids
- Low-noise cryogenic amplifiers

Penning trap

- Four individual Penning traps
- In trap production of ions