# Observation of Spin Flips with a Single Trapped Proton

A. Mooser, *K. Blaum, S. Bräuninger, K. Franke, H. Kracke,*
*C. Leiteritz, W. Quint, C.C. Rodegheri, C. Smorra*
*S. Ulmer and J. Walz*

GSI

HELMHOLTZ
Institut Mainz

RIKEN

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

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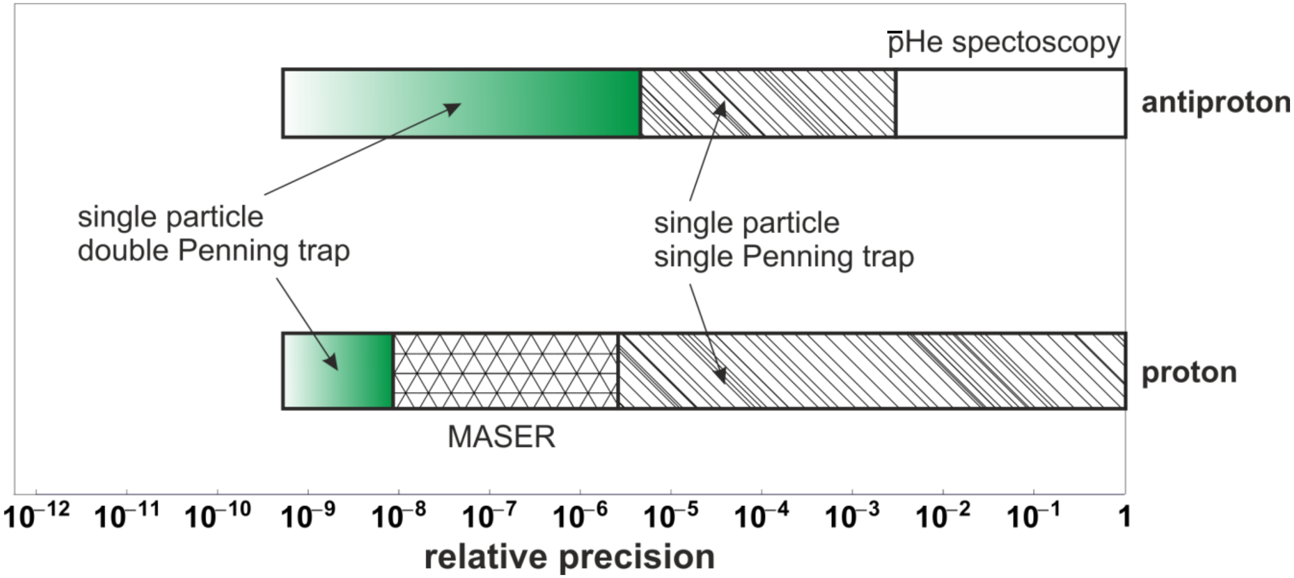
# Motivation

- Precise test of the CPT theorem comparing proton and antiproton g-factor



$$g_{\bar{p}} = 5.585690(24)$$

$$g_p = 5.585694713(46)$$

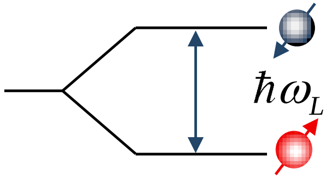
P. F. Winkler *et al.*, Phys. Rev. A **5**, p. 83 (1972).
J. DiSciacca *et al.*, Phys. Rev. Lett. **110**, 130801 (2013).

- Here, aim first direct ppb measurement of proton g-factor

# Determination of the g-factor

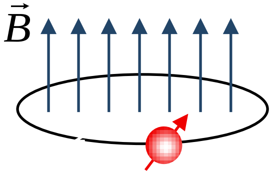
Determination of Larmor frequency in a given magnetic field

$$\omega_L = g\frac{e}{2m_p}B$$



Monitoring magnetic field
via simultaneous measurement
of the free cyclotron frequency

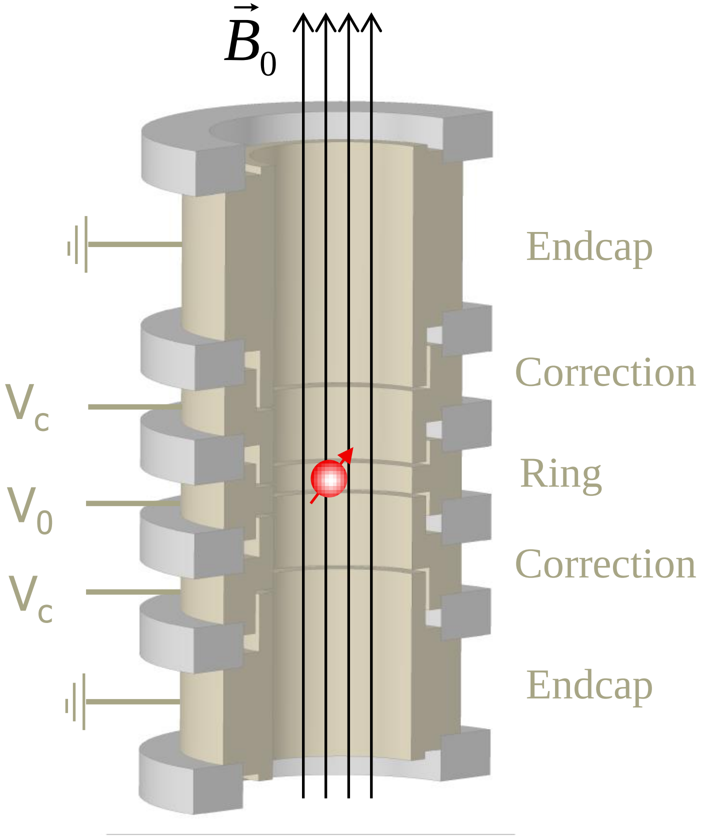
$$\omega_c = \frac{e}{m_p}B$$



$$g = 2\frac{\omega_L}{\omega_c} = 2\frac{\nu_L}{\nu_c}$$

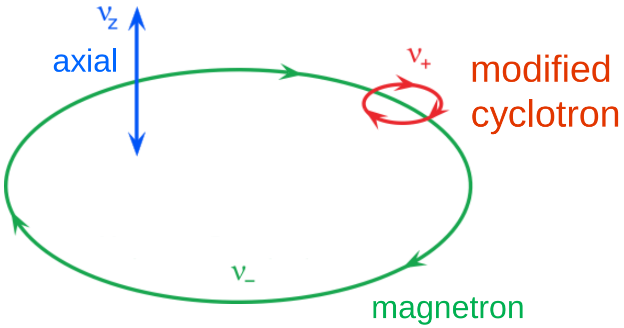
# The Penning trap

Superposition of homogeneous magnetic field and electrostatic quadrupole potential



$\vec{B} = B\vec{e}_z$ → radial confinement

$\Phi(z,\rho) = U_0 c_2 \left( z^2 - \frac{\rho^2}{2} \right)$ → axial confinement



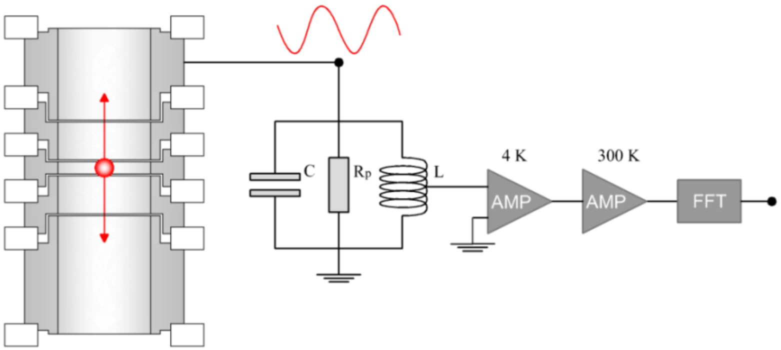
| | |
|---|---|
| axial | $\nu_z = 700\,\mathrm{kHz}$ |
| modified cyclotron | $\nu_+ = 29\,\mathrm{MHz}$ |
| magnetron | $\nu_- = 10\,\mathrm{kHz}$ |

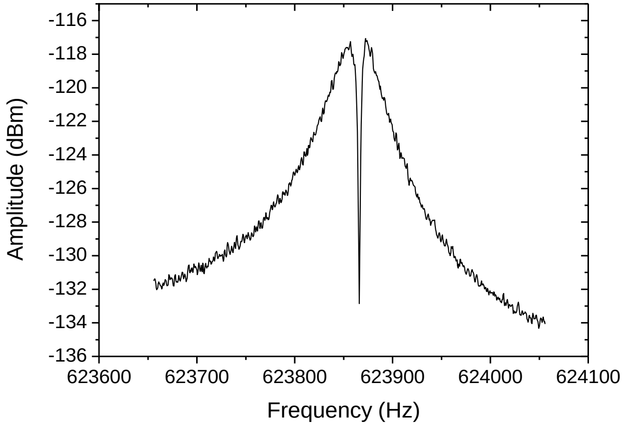
**Invariance Theorem:** $\nu_c^2 = \nu_-^2 + \nu_z^2 + \nu_+^2$

[L. S. Brown and G. Gabrielse, Phys. Rev. A, 25:2423, 1982.]

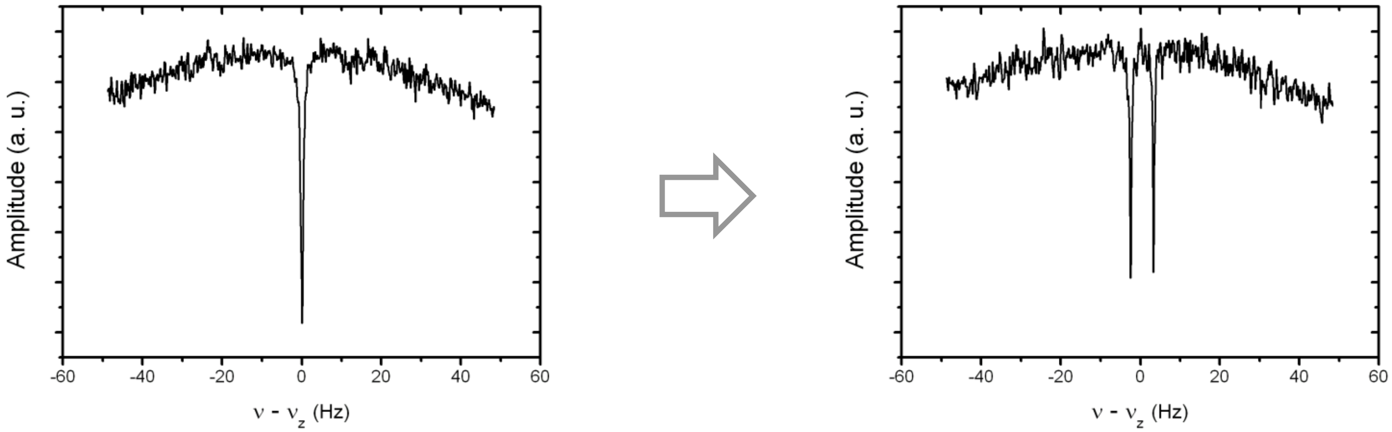
# Measurement of eigenfrequencies

- Image current detection using parallel tuned circuit





- Coupling of modes via rf-sideband coupling, $\nu_{rf} = \nu_+ - \nu_z$ or $\nu_{rf} = \nu_z + \nu_-$
- Amplitude modulation of the axial motion



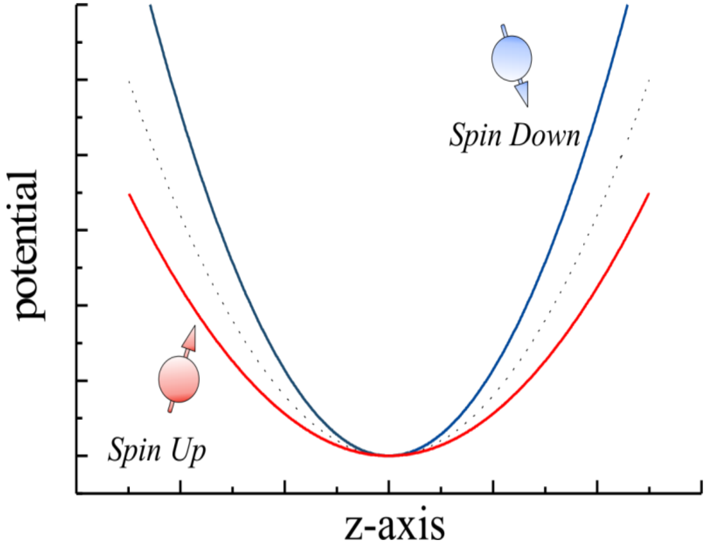
- Measurement of free cyclotron frequency with precision of ppb

# Detection of the spin state

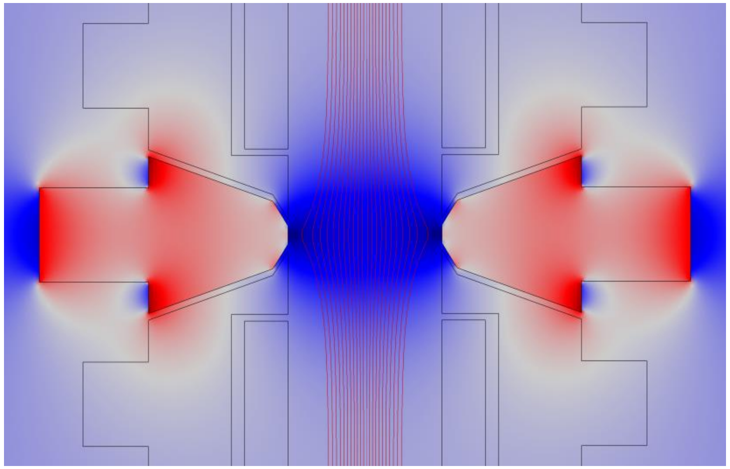
## The continuous Stern-Gerlach effect

Introduce magnetic inhomogeneity, the magnetic bottle…

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

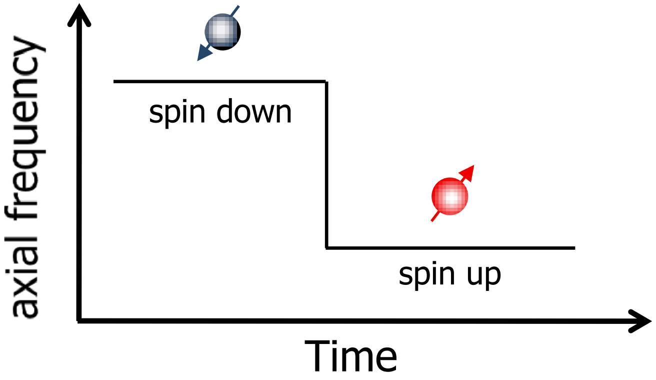


…leading to a shift of the axial frequency



…which adds spin dependent quadratic potential to axial potential…

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



# Detection of spin state

## Challenge

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m}2c_2V_0}$$

electrostatic
potential

$$\pm\frac{1}{2\pi^2\nu_{z,0}}\frac{\mu_z}{m}B_2$$

spin
momentum

$$+\frac{1}{2\pi\nu_{z,0}}\frac{B_2}{B_0}E_{radial}$$

radial angular
momentum

Dealing with nuclear momentum requires huge magnetic bottle of

$$\boxed{B_2 = 30\,\mathrm{T/cm}^2}$$

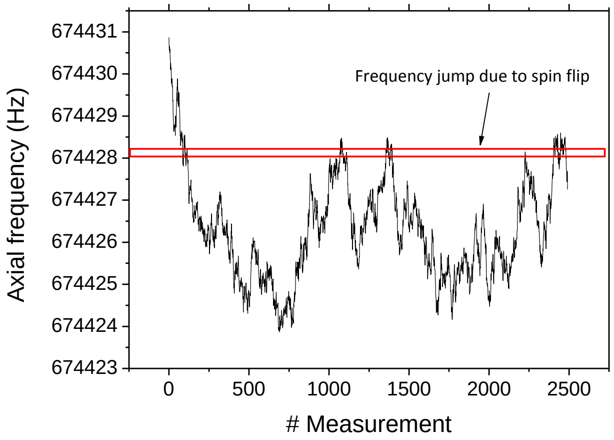
to obtain frequency jump due to spin transition of

$$\boxed{\Delta\nu_z = 190\,\mathrm{mHz} \rightarrow \Delta\nu_z/\nu_z = 2*10^{-7}}$$

**Challenging!**
**Tiny energy fluctuations in radial modes cause huge axial frequency shifts**

$$\boxed{\Delta\nu_z / E_+ = 1\,\mathrm{Hz/\mu eV}^{-1}}$$

# Statistical measurement of g-factor in inhomogeneous magnetic field



$$\Delta\nu_z = (\nu_z(t+T) - \nu_z(t))$$

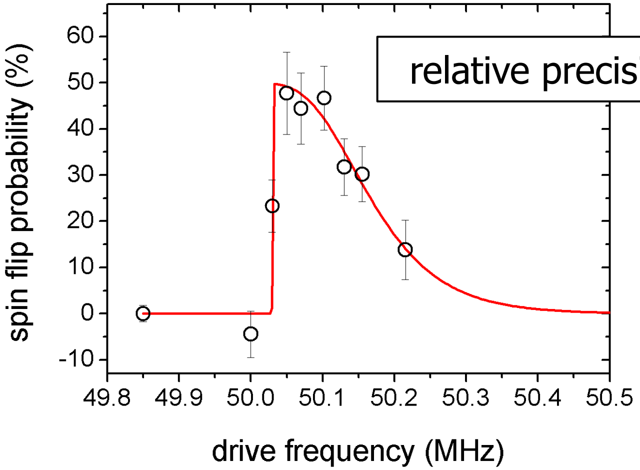
$$\Xi^2 = \frac{1}{n}\sum(\Delta\nu_z - \overline{\Delta\nu_z})^2$$

$\Xi = 150$mHz - not stable enough for observation single spin transition

Axial frequency fluctuation $\Xi$ increases due to spin transitions

Detecting spin transitions in a statistical measurement!

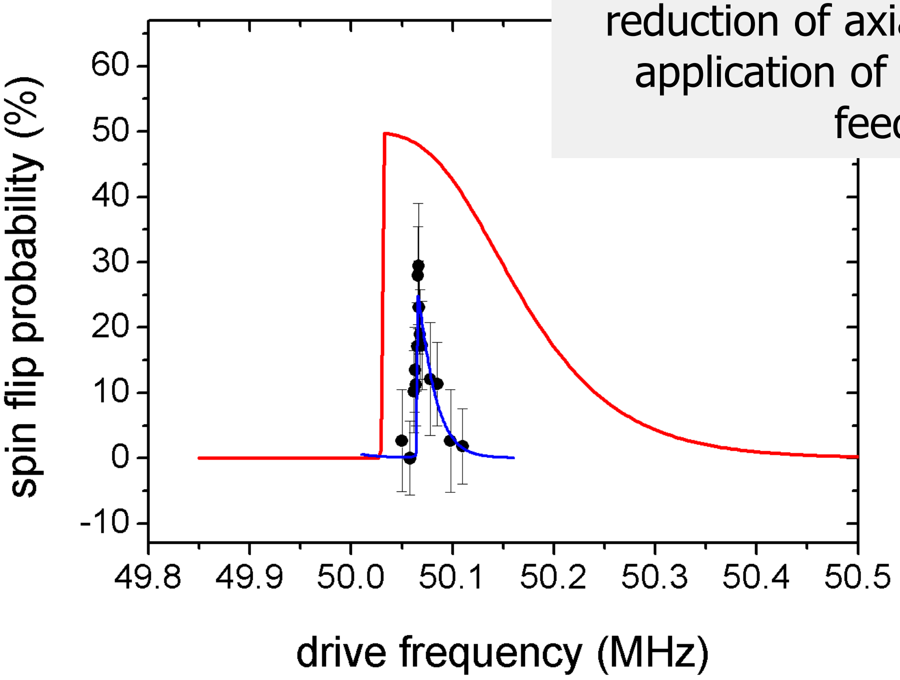
$$\Xi_{SF} = \sqrt{\Xi_{ref}^2 + P_{SF}\Delta\nu_{z,SF}^2}$$



relative precision of $10^{-4}$

S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, J. Walz , Phys. Rev. Lett 106, 253001 (2011)

# g-Factor measurement



reduction of axial temperature by application of active electronic feedback

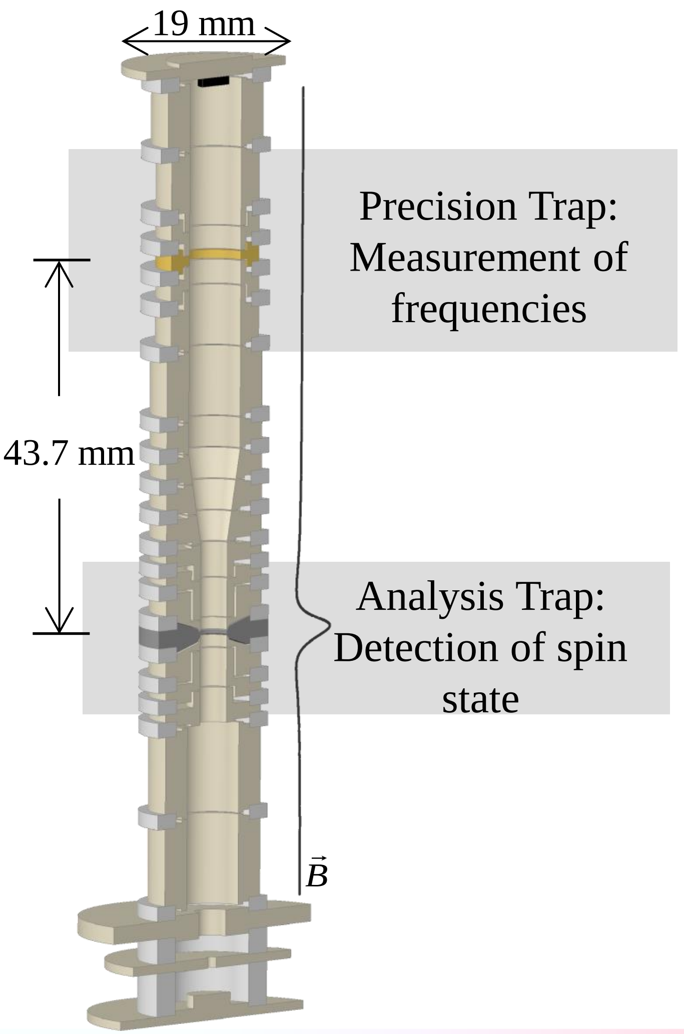
- Larmor frequency measurement with a relative uncertainty of $1.8*10^{-6}$
    - With cyclotron frequency measurement

**g = 5.585 696 (50)**

C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, S. Ulmer, J. Walz , *New J. Phys.* **14** 063011 (2012)

# Double Penning trap technique

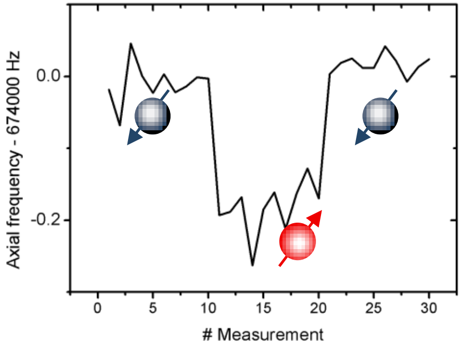
- High Precision measurement demands homogeneous magnetic field
- Introduce two traps – double Penning trap setup (*H. Häffner, Phys. Rev. Lett.85, 5308 (2000)*)



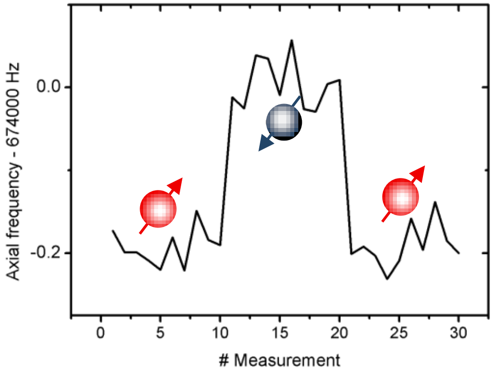
Precision Trap:
Measurement of
frequencies

Analysis Trap:
Detection of spin
state

I. Determination of Spin State

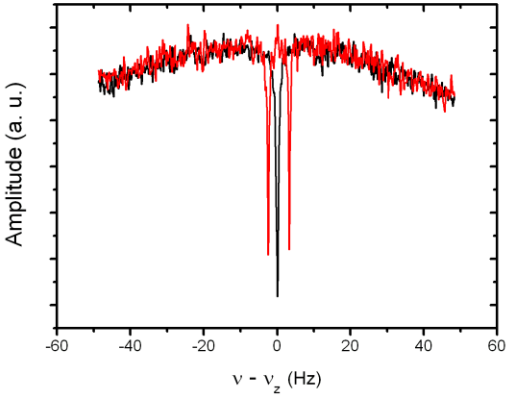


V. Determination of Spin State



II. Transport
to PT

III. Driving Spin & Determining B-Field

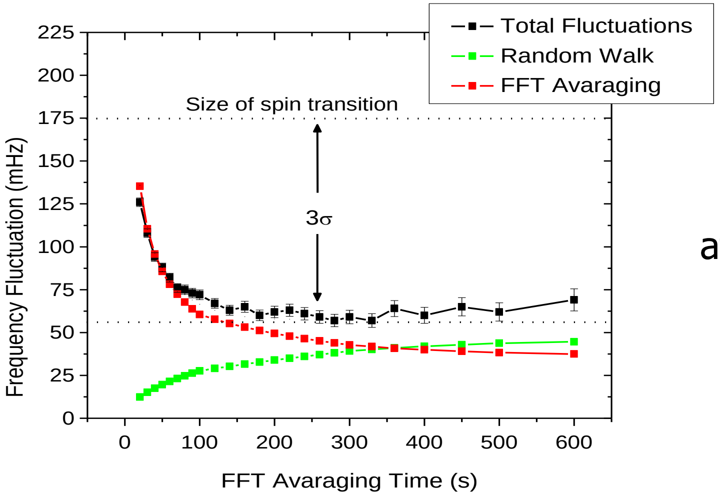


IV. Transport
to AT

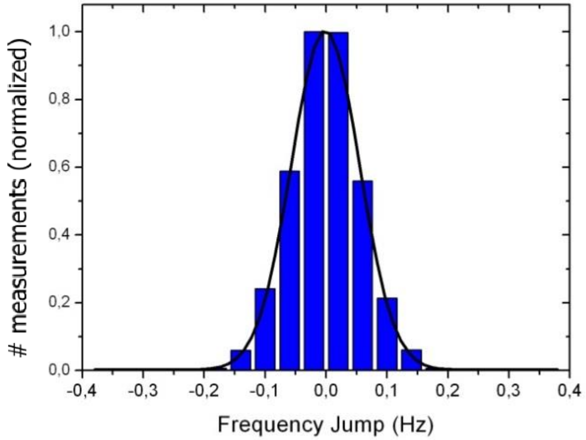
Demands detection of single spin flip –
higher frequency stability necessary

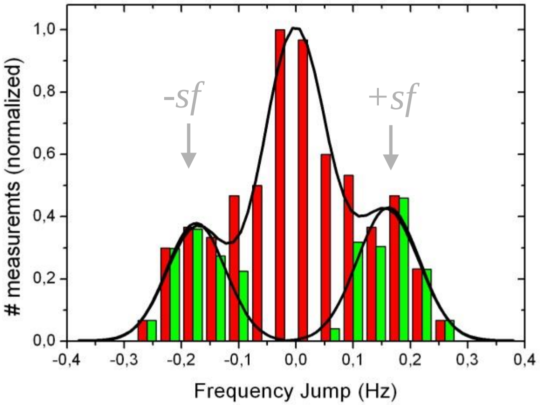
# Improvement of frequency stability in magnetic bottle

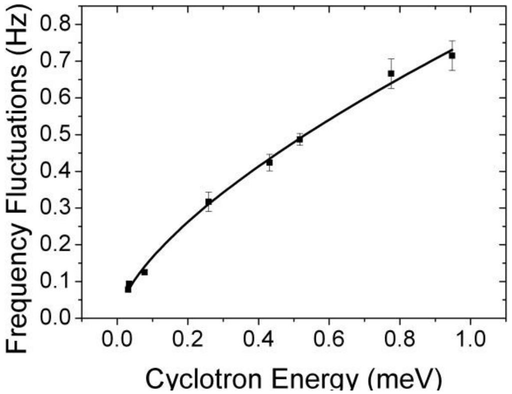
Increasing frequency stability – e.g. advanced detection system



at optimum





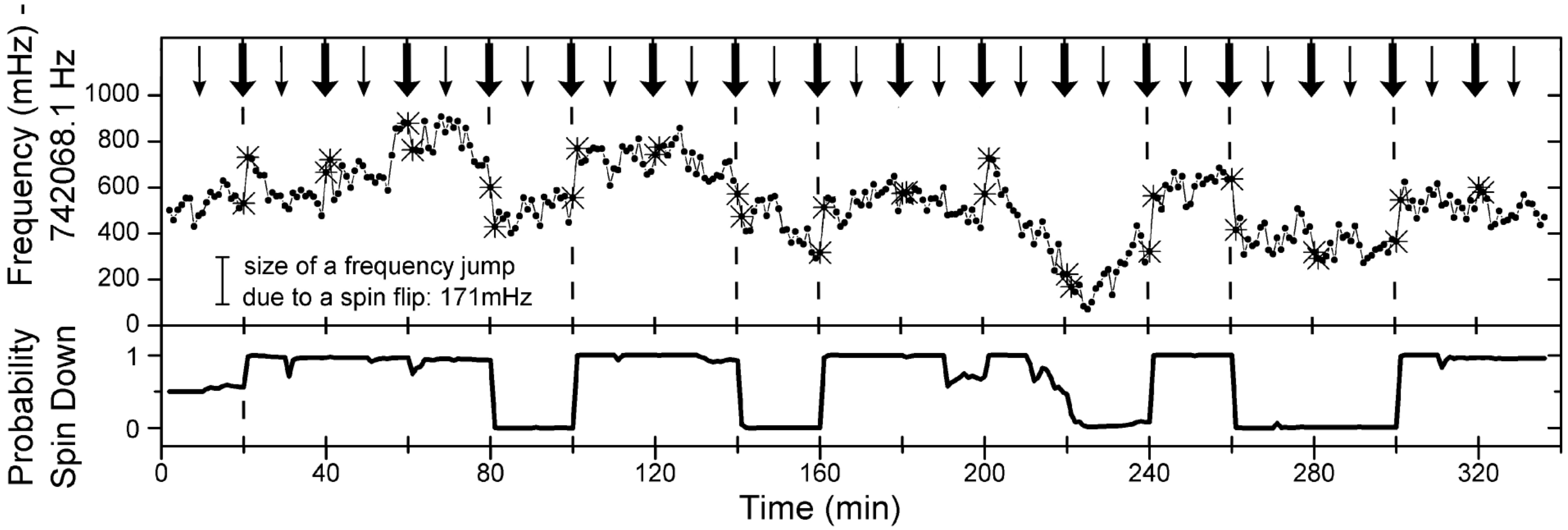


$\Xi_{opt} = 55 mHz$ Under ideal conditions - low cyclotron energies

Spin state can be detected with high probability at low energies

# Observation of single spin flips

- Series of axial frequency measurements in AT
- Apply resonant and off-resonant spin flip drives – background check



- Determination of spin state using Bayes theorem – conditional probabilities
- No significant jumps at off-resonant drive

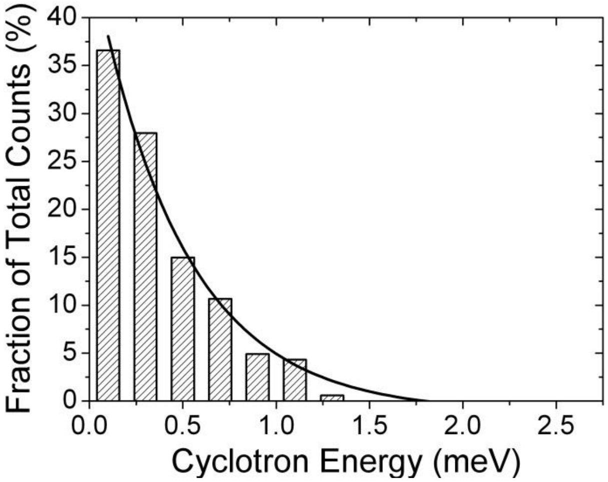
Fidelity of 88% - fraction of correctly assigned spin states in a series of measurement in analysis trap

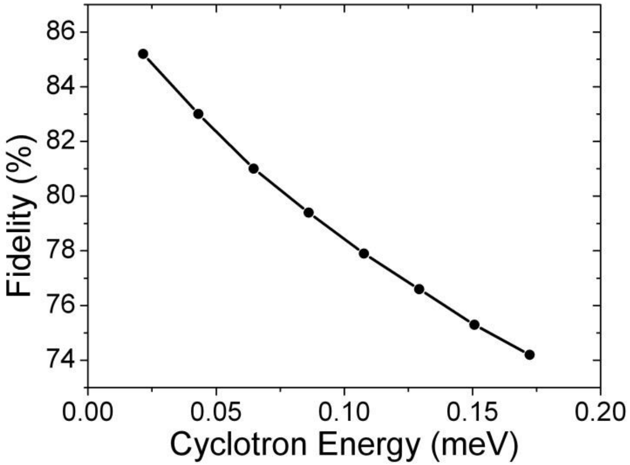
A. Mooser *et al.,* Phys. Rev. Lett. **110**, 140405 (2013).

Related observations are discussed in J. DiSciacca *et al.,* Phys. Rev. Lett. **110**, 140406 (2013).

# Towards the double trap technique

- Cyclotron frequency measurement in PT demands heating of cyclotron mode
- Low energies are needed in AT for high fidelity spin state detection
- Preparation at low energy by coupling to thermal bath of cyclotron detector in PT and transport to AT - statistical process





Fidelity: fraction of correctly assigned spin flips in precision trap

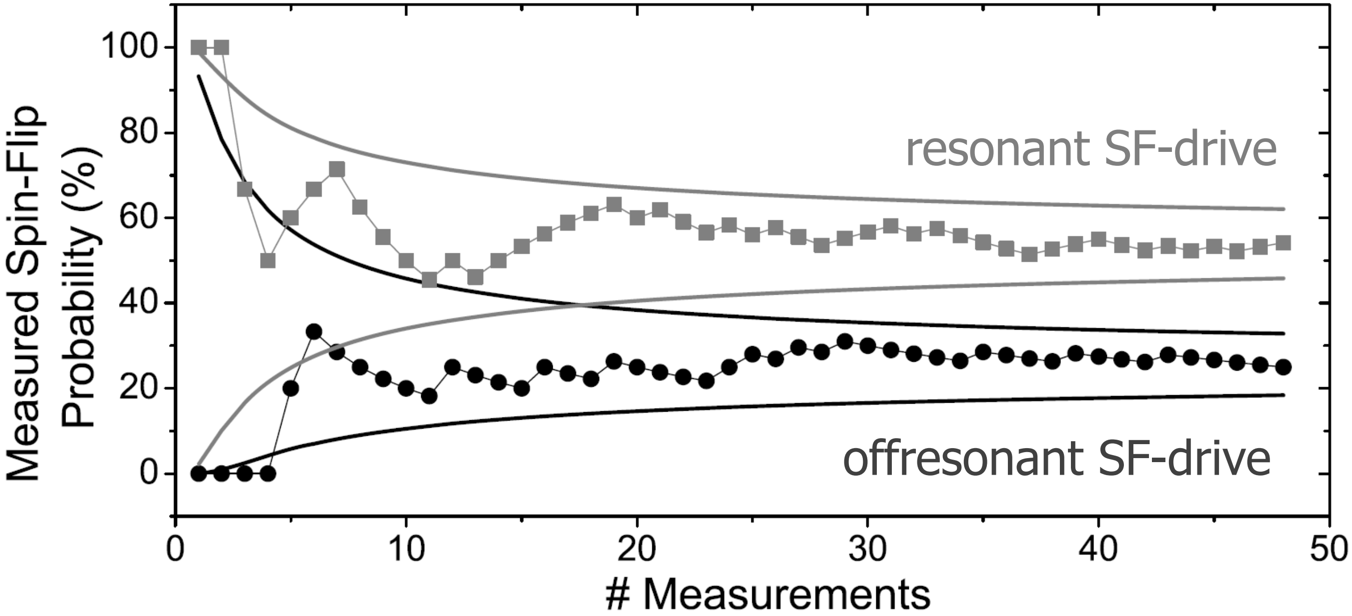
lower statistics at higher fidelity ⟷ higher statistics at lower fidelity

3 hours for one spin flip trail in PT at fidelity of 75%

# Demonstration of double trap technique

Measurement:
- Detect spin state - magnetic bottle in analysis trap
- Excite spin transition in precision trap
- Detect spin state - magnetic bottle in analysis trap

**Observation of spin flips excited in the homogeneous magnetic field of the PT**



g-factor measurement with precision of $10^{-9}$ in reach

A. Mooser *et al.*, Phys. Lett. B **723**, 78–81 (2013).

# Thank you for your attention

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*VH-NG-037*

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***Adv. Grant MEFUCO (#290870)***

# Quality of spin state detection

## Bayes and threshold method

Threshold method: Accept spin flip if frequency jump above given threshold

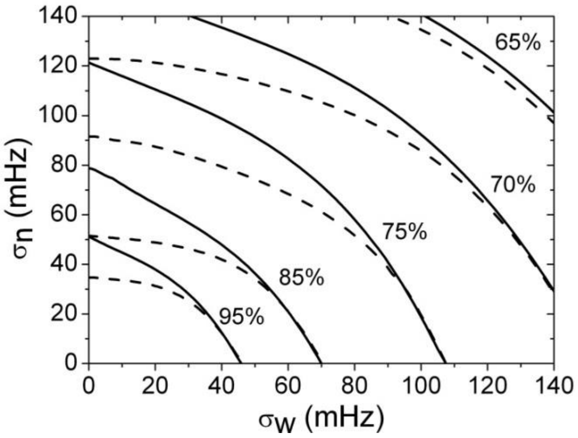
Bayes rule – conditional probability of having a spin state

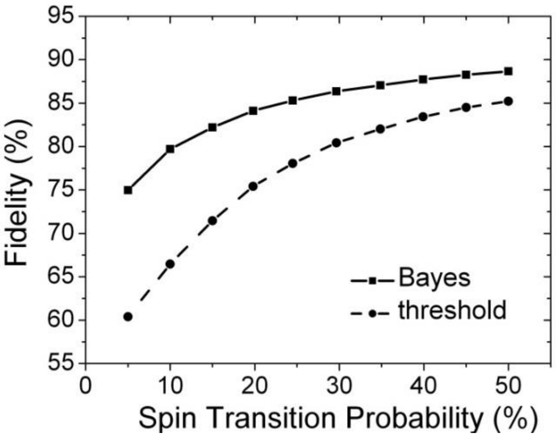
$$f_i = W_i + n_i \pm \Delta\nu_{z,sf} \quad W_i = \sum w_i$$

$$P(\uparrow_i, W_i \mid f_i, f_{i-1}, \ldots) \propto P(f_i \mid \uparrow_i, W_i, f_{i-1}, \ldots) * P(\uparrow_i, W_i \mid f_{i-1}, \ldots)$$

Update of state probability given complete frequency, noise and previous state information

Fidelity: fraction of correctly assigned spin states in a series of measurements





Bayes method superior to threshold method - Optimal fidelity of 88%