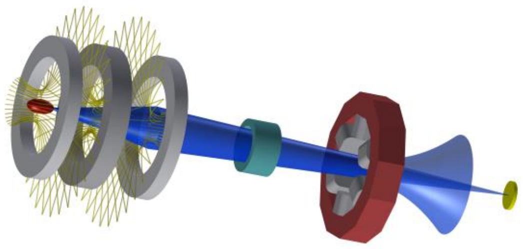
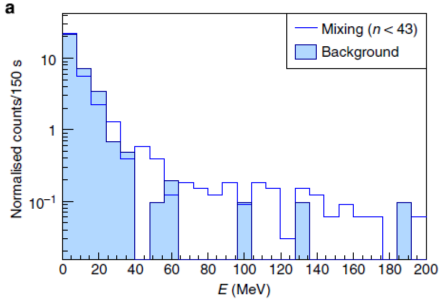
Precision Physics and Antimatter

Part 4 - Magnetic Moments

Summary Yesterday

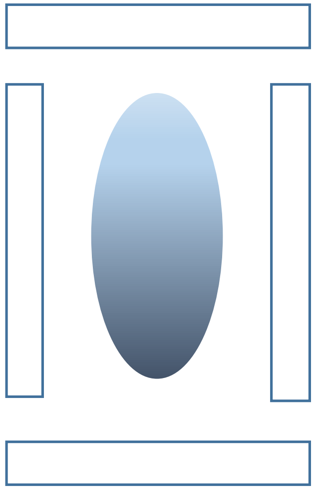
Asacusa



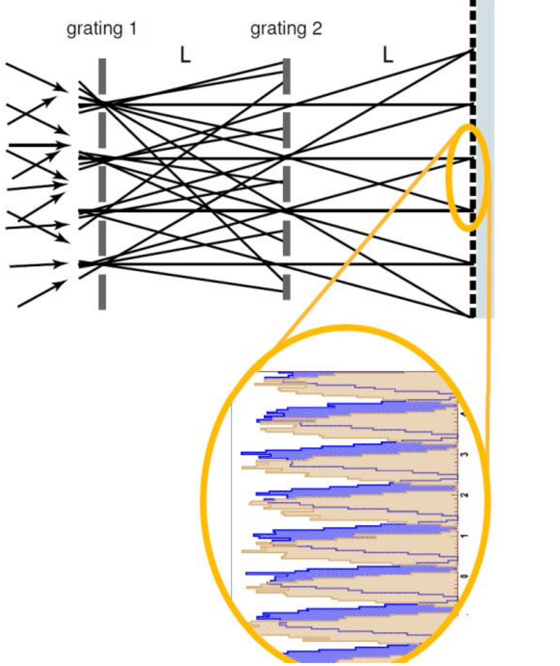


ALPHA-g

Magnetic antihydrogen trap

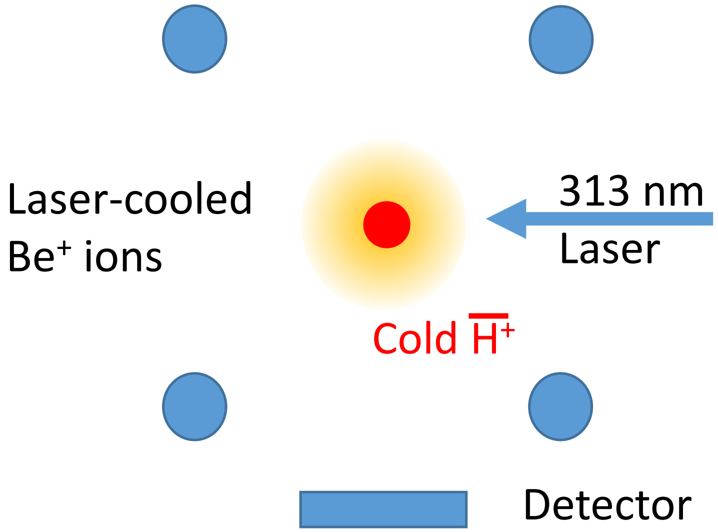


AEgIS

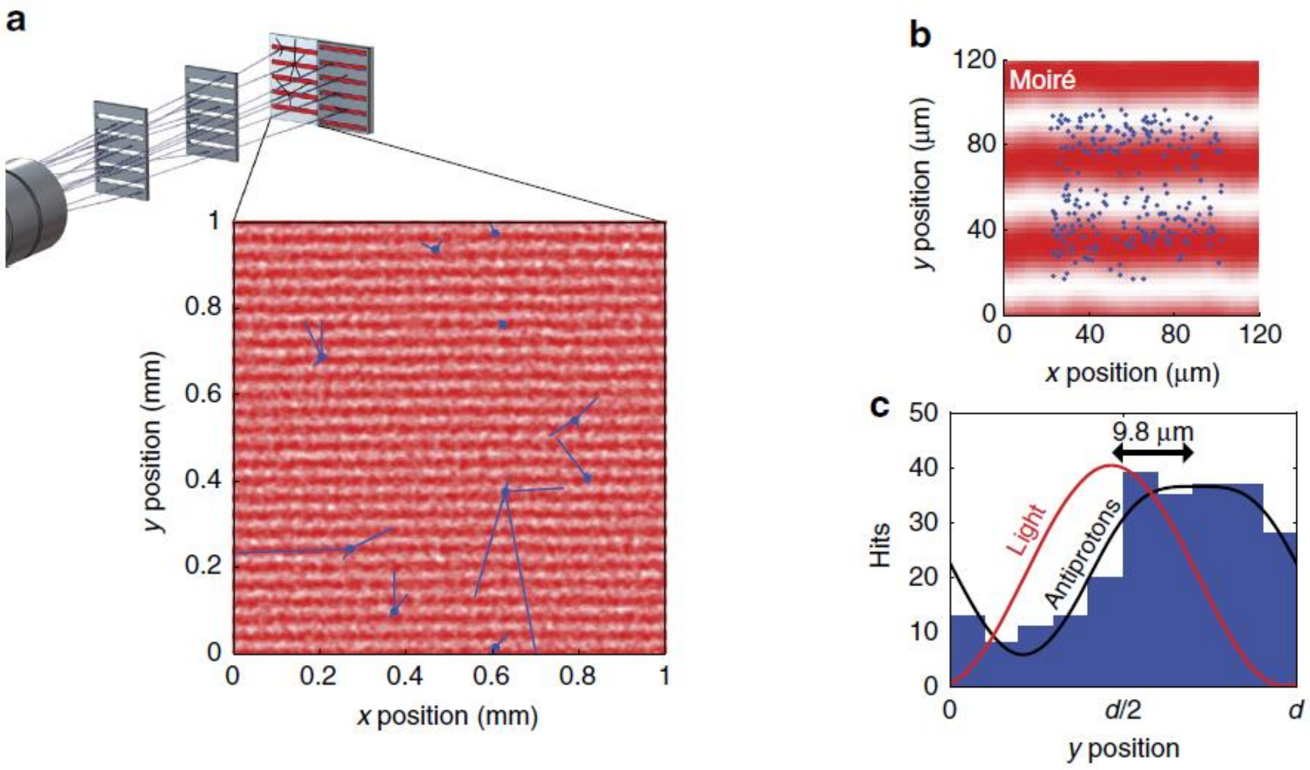


GBAR

Radiofrequency trap



Questions



S. Aghion, *et al. Nature Communications* **5**, 4538 (2014)

Force acting on antiprotons

F=530±50 aN (stat.) 10^{-18}

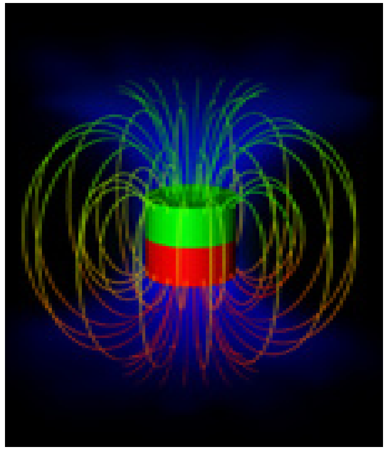
Diverging beam – charged particles

Gravitation acting on antiprotons

$F=10^{-26}$ N

Expected to gain 11 orders of magnitude with cooled hydrogen beam

Fundamental particles Behave like a small magnet

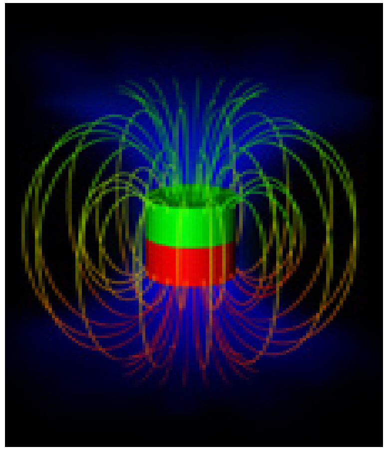


The magnetic moment

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

Every spin caring particle has a magnetic moment

What to learn from magnetic moments?



Test of fundamental physical laws

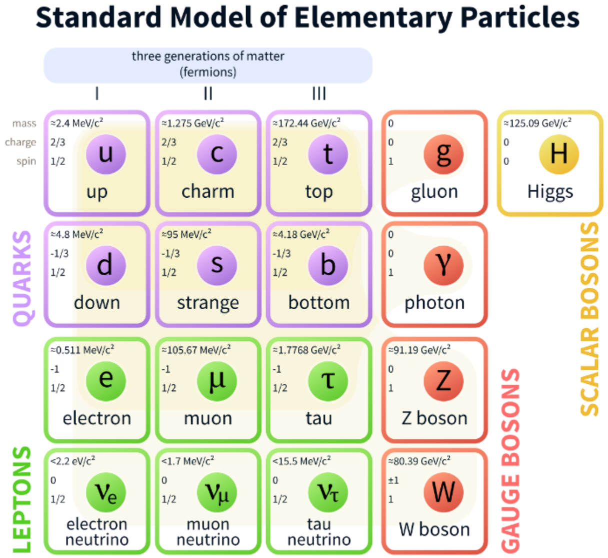
Searches for physics beyond the Standard Model

Determination of fundamental constants

What to learn from magnetic moments?

Test of fundamental laws

- QED
- Bound-state QED
- QCD
- Electro-weak

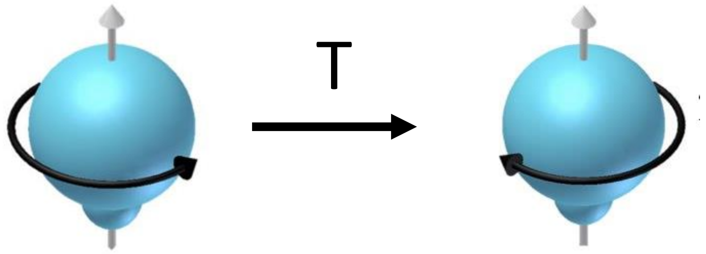


Determination of Fundamental constants

- Magnetic moment
- Finestructure constant
- Rydberg constant
- Electron mass
- Charge radii

Searches for physics beyond the Standard Model

- CPT-invariance
- Searches for EDM
- Fifth Forces



Outline

- Electron and positron
  - Muon and antimuon
    - Proton and antiproton
      - Sympathetic laser cooling of protons/antiprotons
        - G-Factor in highly charged ions

Electron and Positron

Equations of motions

$$\vec{B} = B_0 \vec{e}_z$$

$$V(z,\rho) = V_0 C_2 (z^2 - {\rho^2}/{2})$$

Newton's equation of motion:

$$m\ddot{\vec{x}} = -q\vec{\nabla}V(r,\rho) + q\dot{\vec{x}} \times \vec{B}$$

z-Direction: Harmonic Oscillator

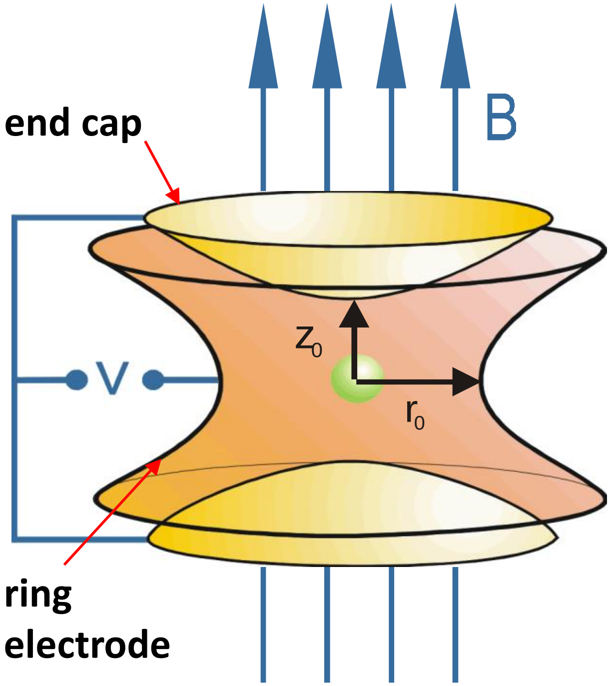
r-Direction: Coupled DEQ due to Lorentz-force

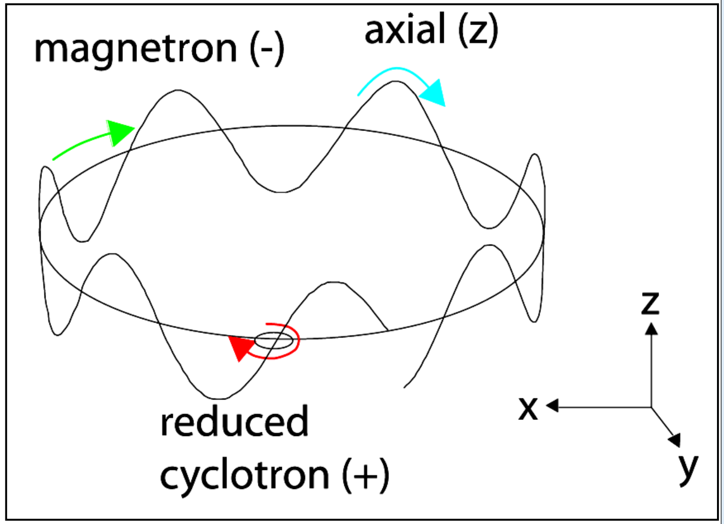
$u = x + iy$ ⇒ $\ddot{u} = \frac{1}{2}\omega_z^2 u - i\omega_c \dot{u}$ ⇒ Ans.: $u = u_0 e^{-i\omega t}$

⇒ $0 = \omega^2 - \omega\omega_c + \frac{1}{2}\omega_z^2$

Two frequencies solve this equation: $\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$

The Penning trap





$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{qV}{md^2}}$$

$$\nu_+ = \frac{\nu_c}{2} + \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$

$$\nu_- = \frac{\nu_c}{2} - \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$

$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

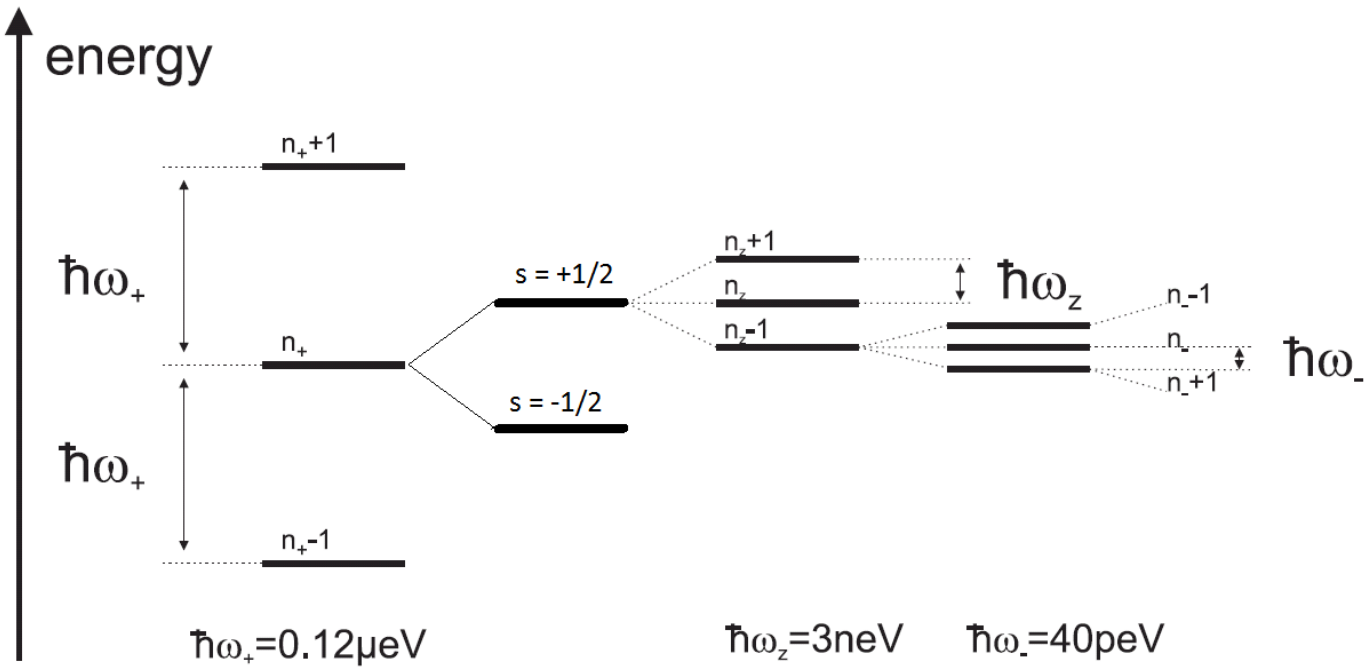
Level scheme of the quantized Penning trap

- Some further calculations lead to the quantized Hamiltonian:

$$
\begin{aligned}
H \;=\; & \hbar\omega_+ \left(A_+^\dagger(t) A_+(t) + \frac{1}{2} \cdot \mathbb{1} \right) - \hbar\omega_- \left(A_-^\dagger(t) A_-(t) + \frac{1}{2} \cdot \mathbb{1} \right) \\
& + \hbar\omega_z \left(A_3^\dagger(t) A_3(t) + \frac{1}{2} \cdot \mathbb{1} \right) .
\end{aligned}
$$

- “Geonium atom”:

$$\psi_{s,n_+,n_-,n_z}$$

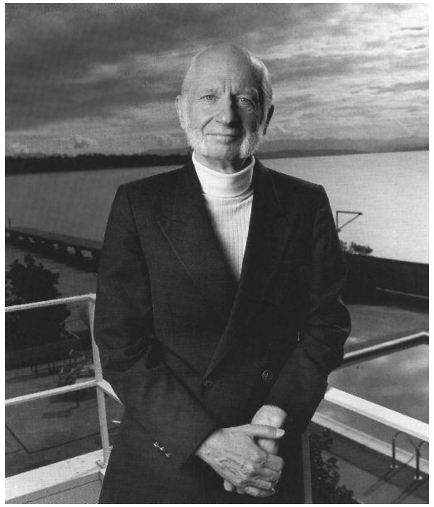


Electron and Positron g-Faktor

Precise comparison of the magnetic moment of the electron and the positron

- First high precision experiment performed in a Penning trap
- First high precision experiment performed with trapped Antimatter
- Most precise test of Quantum-Electro-Dynamics
- Most precise measurement of the fine structure constant

Hans Dehmelt
Nobel price 1989



Contuinued by
Gerald Gabrielse

What is the g-Faktor

- Dirac equation:

$$i\hbar \frac{\partial}{\partial t} \Psi = \left(\beta mc^2 + c \sum \alpha_i p_i \right) \Psi \qquad \text{with } \beta = \begin{pmatrix} \mathbb{I} & 0 \\ 0 & -\mathbb{I} \end{pmatrix} \text{ and } \alpha_i = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix}$$

Pauli matrices

- Minimal Substitution

$$i\hbar \frac{\partial}{\partial t} \rightarrow i\hbar \frac{\partial}{\partial t} + \mathrm{e}\Phi \qquad p_i \rightarrow p_i - \mathrm{e}\vec{A}$$

- Pauli euquation of spin carring particle in E and B fields

$$i\hbar \frac{\partial}{\partial t} \Psi = \left(\frac{(\vec{p} - e\vec{A})^2}{2\,m} + \mathrm{e}\Phi - \frac{e\,\hbar}{2\,m} \vec{\sigma} \cdot \vec{B} \right) \Psi$$

What is the g-Faktor

- Pauli euquation of spin carring particle in E and B fields

$$i\hbar \frac{\partial}{\partial t} \Psi = \left(\frac{(\vec{p} - e\vec{A})^2}{2\,m} + \mathrm{e}\Phi \boxed{- \frac{e\,\hbar}{2\,m}\,\vec{\sigma}} \cdot \vec{B} \right) \Psi$$

- Classical momentum

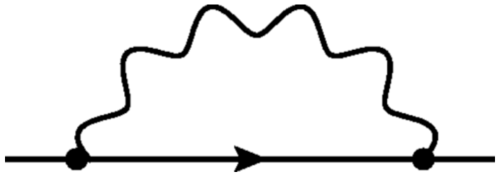
$$\text{with } \vec{S} = \frac{1}{2}\hbar\vec{\sigma} \Rightarrow \overrightarrow{\mu_D} = \frac{e}{\mathrm{m}_p}\vec{S}$$

$$\overrightarrow{\mu_k} = \frac{e}{2\mathrm{m}_p}\vec{S}$$

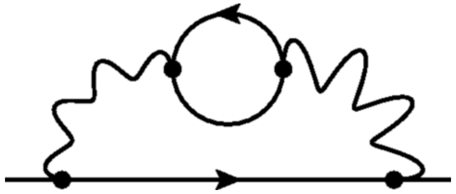
$$\boxed{\overrightarrow{\mu_D} = g\,\overrightarrow{\mu_k} \quad \text{with } g = 2}$$

Not the end of the story

- A “free” Dirac particle -> particle in presence of background field
- Background field fluctuates due to minimum energy of harmonic oscillator vacuum states.

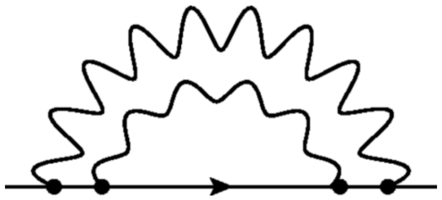


Self Energy 1st order

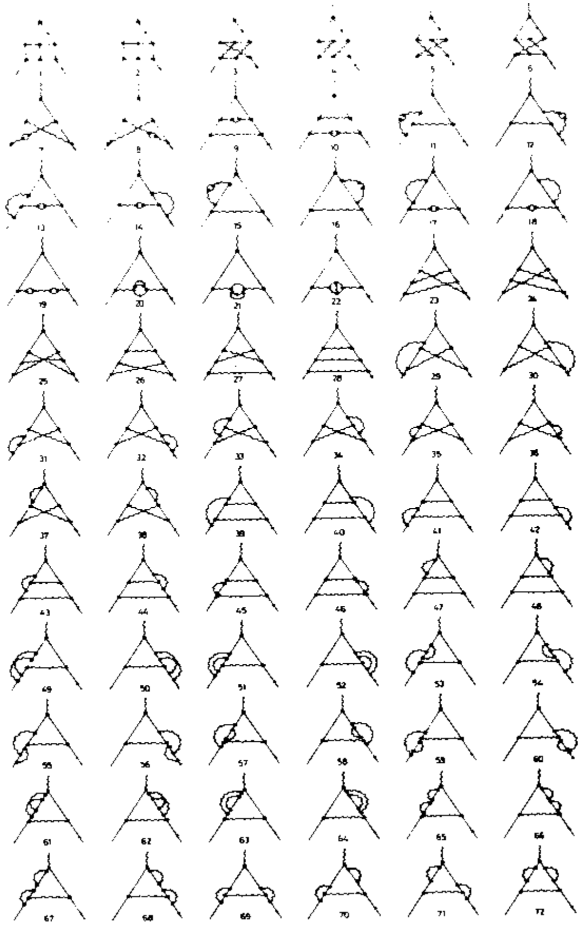


Vacuum polarization

Order?



Self Energy 2nd order



6th order

Electron g-Faktor and QED

- Effects described by Swinger series

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \dots$$
$$+ a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

$$a_e(theo) = \frac{g - 2}{2} = 0{,}0011596521811\,3\,(84)$$

C_2	0,5
C4	-0,328478965579
C6	1,181241456587
C8	-1,9144(35)
$a_{\mu,\tau}$	2,720919(3) 10^{-12}
$a_{hadronic}$	1,682(20) 10^{-12}
a_{weak}	0,0297(5) 10^{-12}

5th order 12 672 diagrams calculated

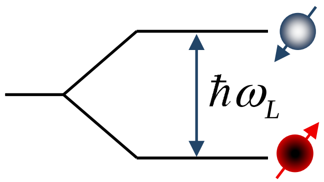
Toichiro Kinoshita

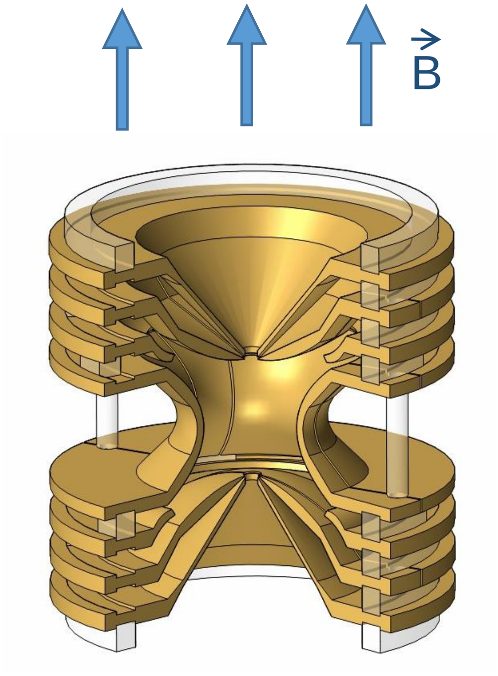
„I am digging at the roots of physics to see whether there is some treasure there.“

Basic Principle for Penning traps

Determination of Larmor frequency in a given magnetic field

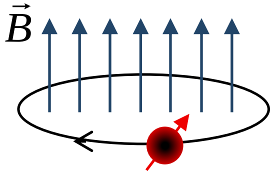
$$\omega_L = \frac{g}{2}\frac{e}{m}B$$





Monitoring magnetic field via simultaneous measurement of the free cyclotron frequency

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

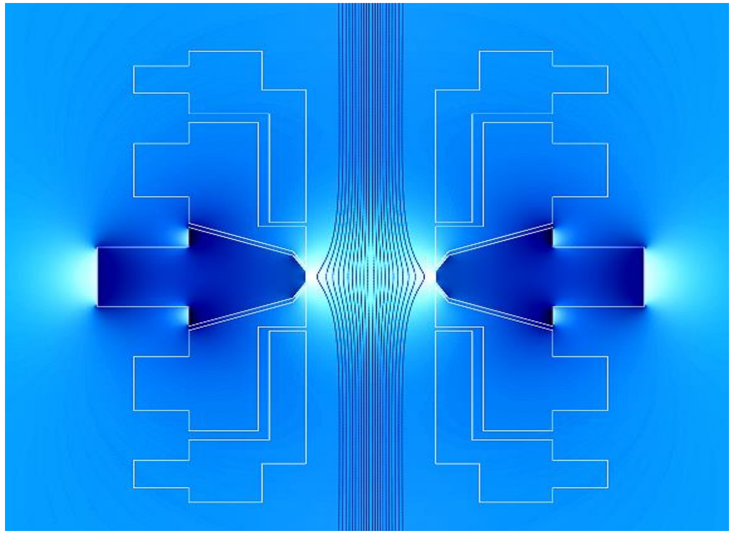


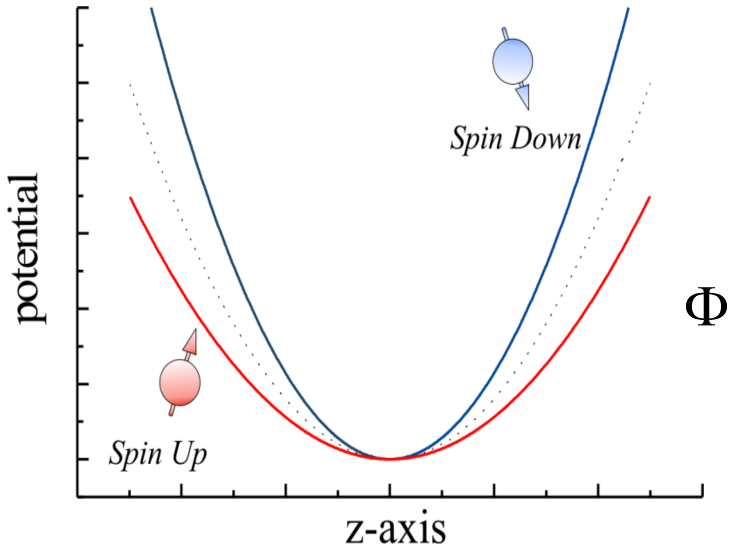
$$g = 2\frac{\omega_L}{\omega_c} = 2\frac{\nu_L}{\nu_c}$$

How to measure the Larmor frequency?

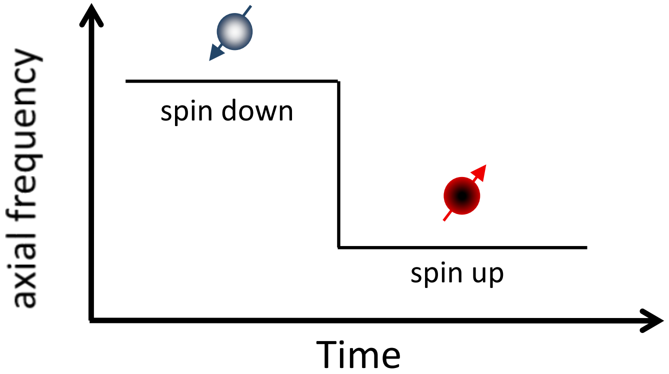
Introduce magnetic inhomogeneity, the magnetic bottle

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





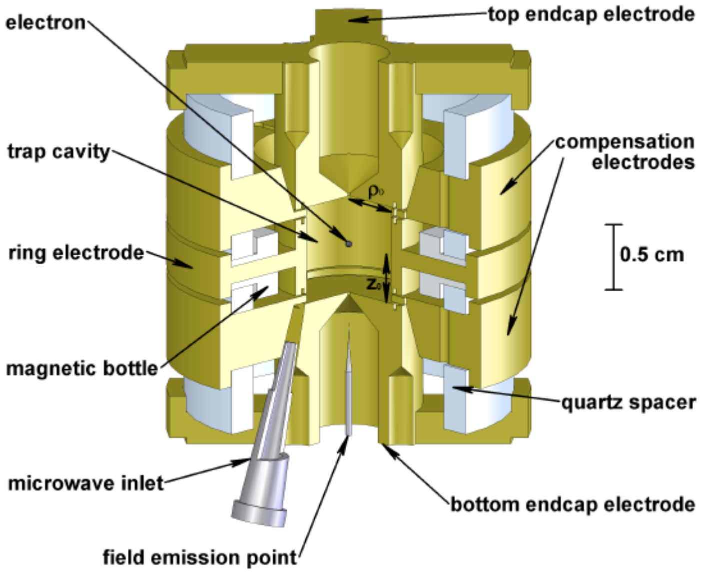
$$\Phi_z = \pm\mu_p B_z$$

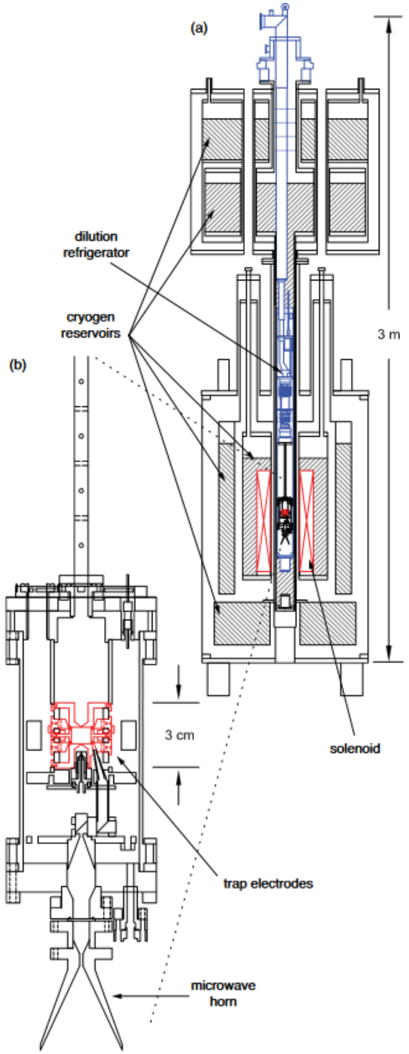


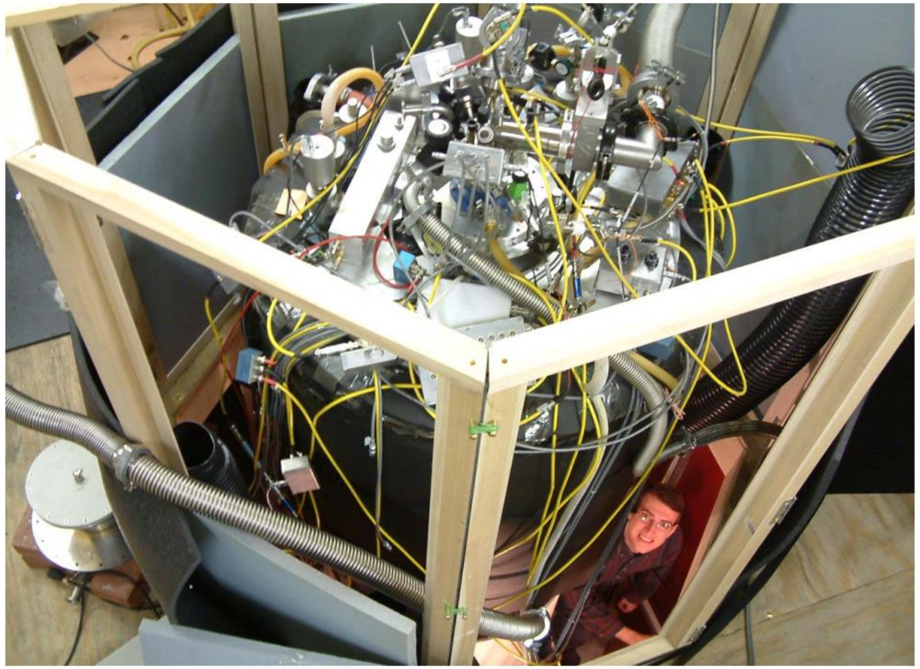
Spin flip results in shift of the axial frequency

$$\nu_z \propto \frac{\mu_p}{m} B_2$$

Setup


electron
top endcap electrode
trap cavity
compensation electrodes
ring electrode
0.5 cm
magnetic bottle
quartz spacer
microwave inlet
bottom endcap electrode
field emission point

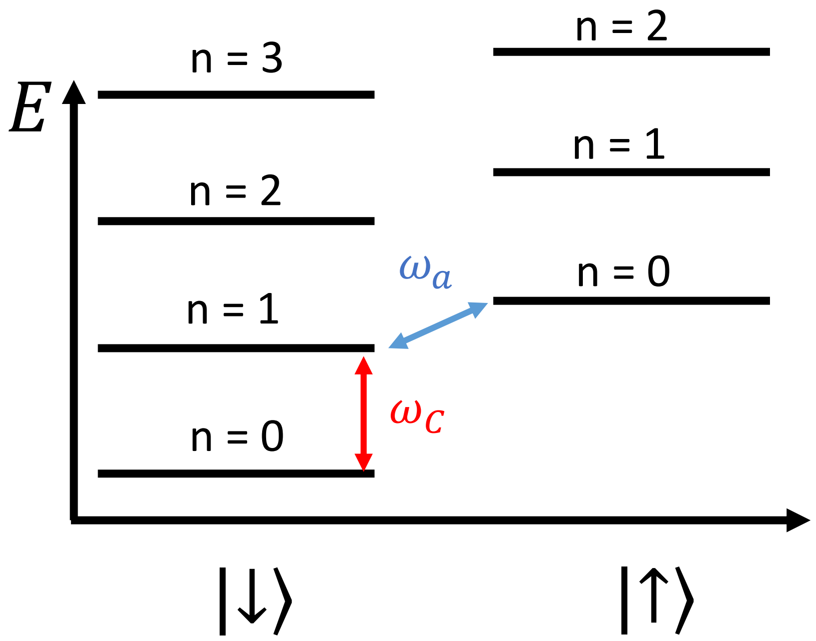

(a)
dilution refrigerator
cryogen reservoirs
3 m
(b)
3 cm
solenoid
trap electrodes
microwave horn



Special Case for Electron

- Don't measure Larmor but so-called Anomalie frequency:

$$\frac{(\omega_L - \omega_C)}{\omega_C} = \frac{\omega_a}{\omega_C} = \frac{g - 2}{2}$$



- Direct measurement of QED corrections

$$\frac{g - 2}{2} = 0{,}00115965218113$$

- Gain 3 orders of precision in *g* for free

Observation of quantum jumps

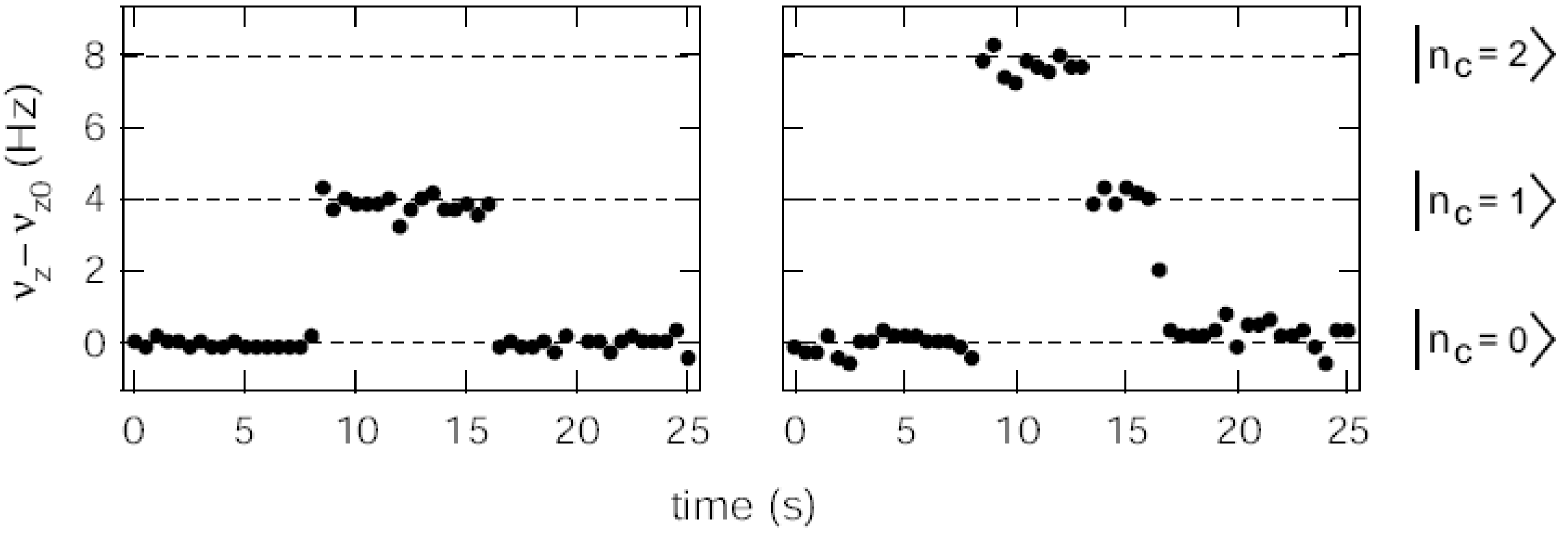


Figure 2.14: Axial frequency shift (with $\nu_z \approx 200$ MHz) caused by quantum cyclotron transitions of a single electron between the ground and first excited state (left) and between the ground and first two excited states (right).

Brian Carl Odom, PhD thesis (2014)

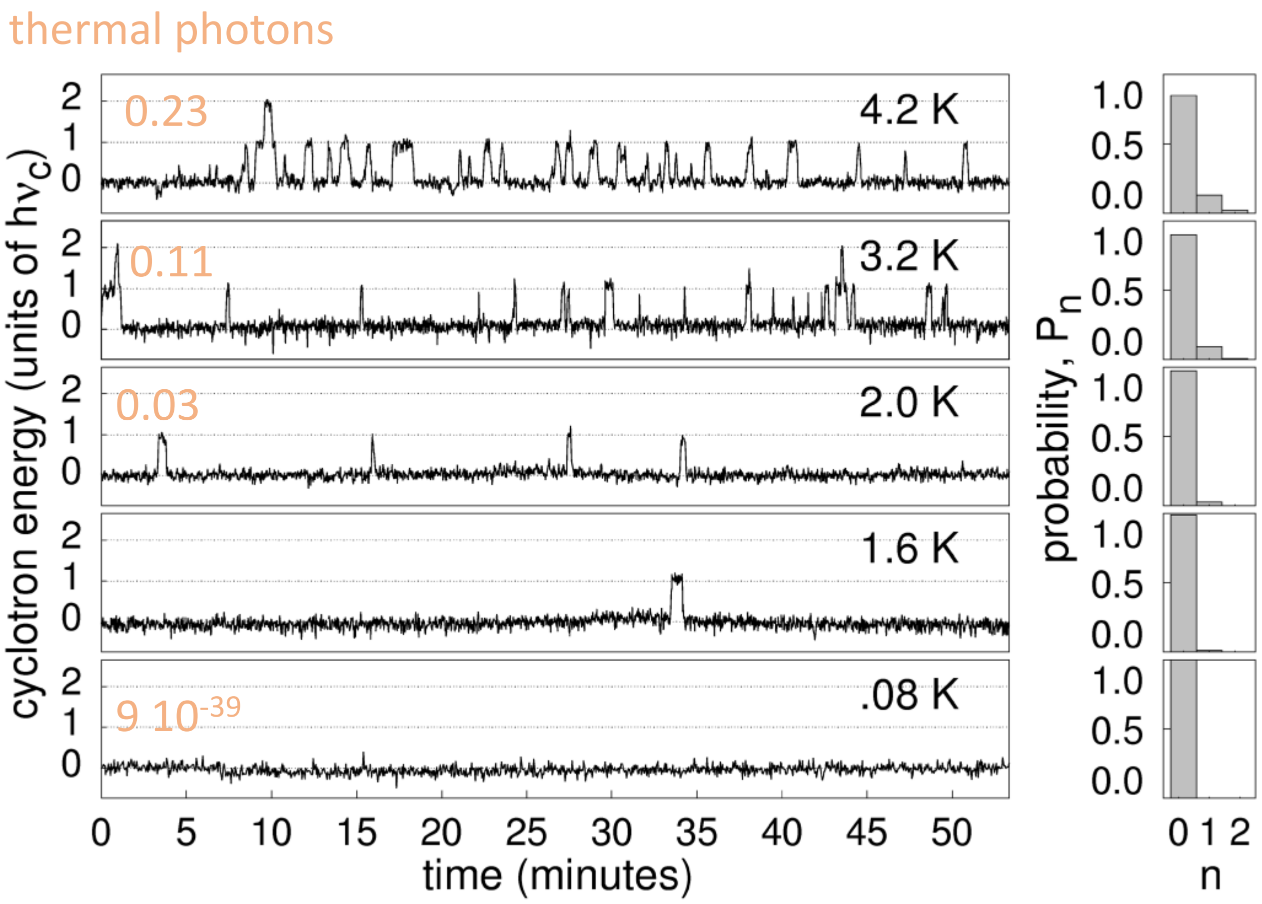
Observation of quantum jumps

Electron cools radiativly to temperature of surrounding

Excited by thermal photons

Temperature reduction: lower thermal photon density

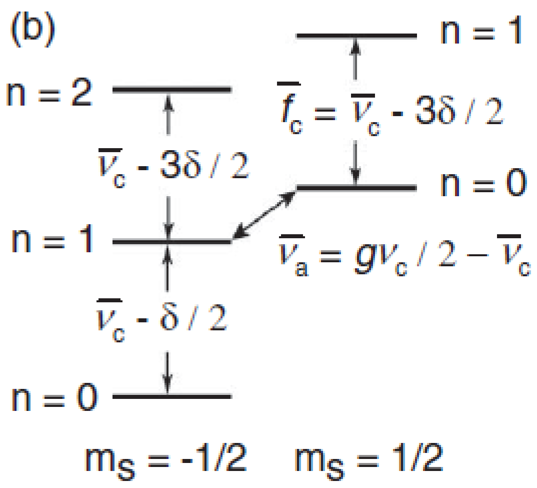
Effectively measured: Axial frequency as a function of time

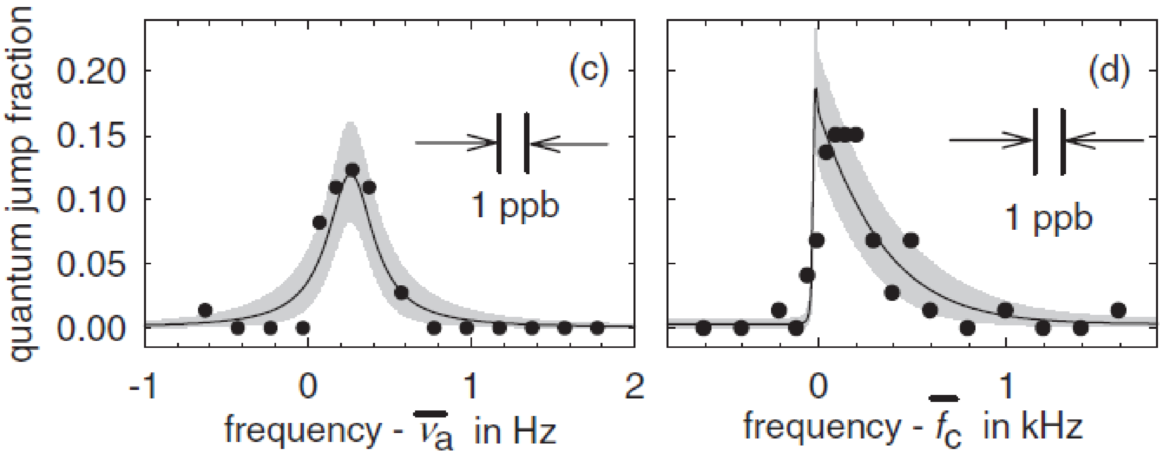


Peil, S. & Gabrielse, G. *Phys. Rev. Lett.* **83** , 1287–1290 (1999).

Measurement Sequence

1. Prepare particle in (0, ½) – state
2. Drive the anomaly transition
3. Anomaly transition to (1, -½) – state
4. Radiative decay to (0, -½)
5. Axial frequency changes





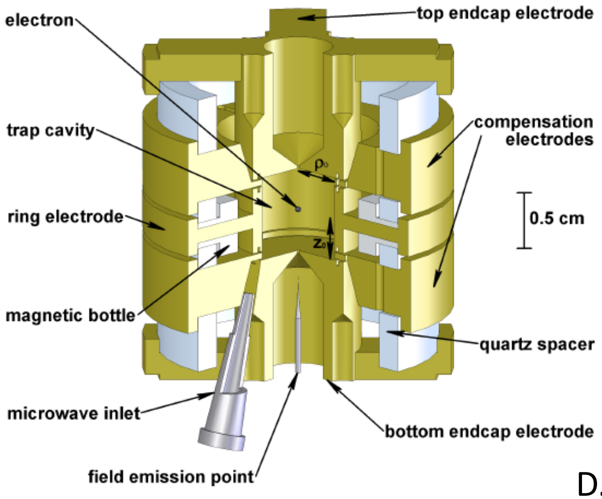
B. Odom, D. Hanneke, B. D'Urso, and G. Gabrielse Phys. Rev. Lett. 97, 030801 (2006)

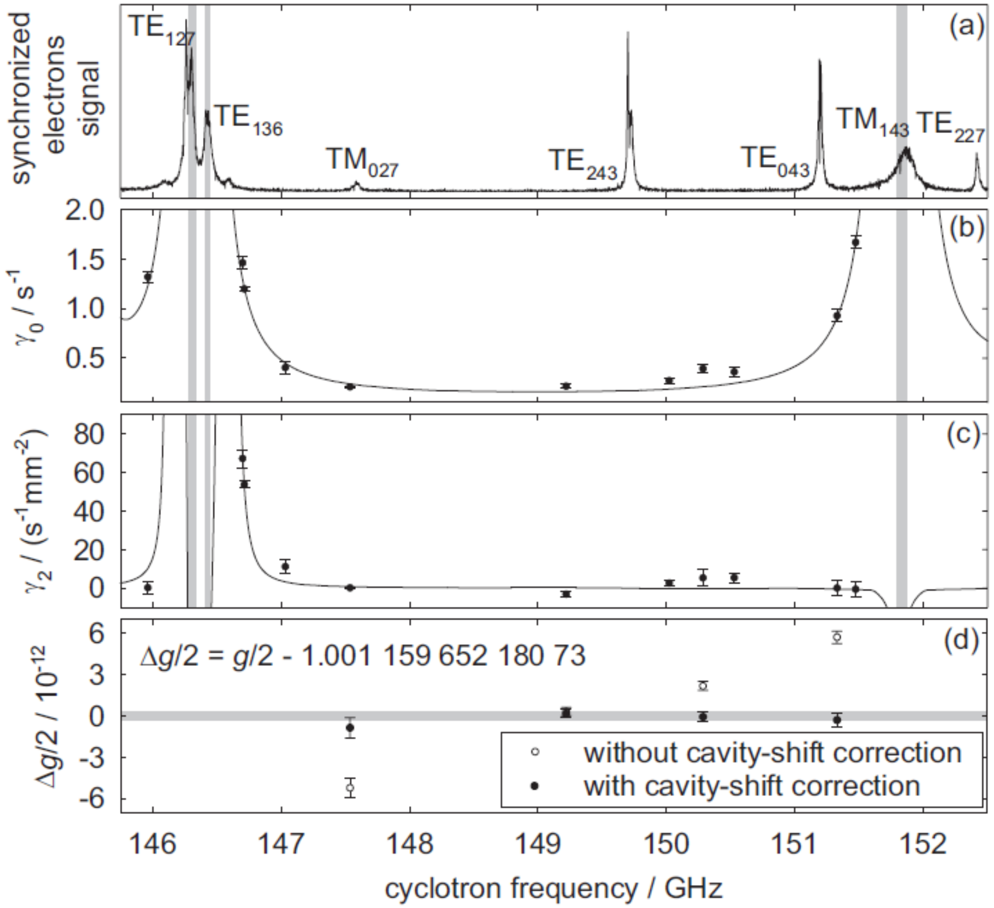
Dominant systematic effect

- Metal electrodes from a resonant microwave cavity – resonant radiation modes
- Modes can couple to the electron cyclotron motion, altering its damping rate and shifting its frequency

$$\bar{\omega}_c = \omega_c \left(1 + \frac{\Delta\omega_c}{\omega_c}\right)$$

- Tune cyclotron frequency out of resonance with modes by changing the magnetic field
- And compare to theory





D. Hanneke, S. Fogwell, and G. Gabrielse Phys. Rev. Lett. 100, 120801 (2008)

After 25 years of development

PRL **100,** 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

D. Hanneke, S. Fogwell, and G. Gabrielse*

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.

DOI: 10.1103/PhysRevLett.100.120801 PACS numbers: 06.20.Jr, 12.20.Fv, 13.40.Em, 14.60.Cd

$$g/2 = 1.001\,159\,652\,180\,73\,(28)\ [0.28\,\text{ppt}]$$

Most precise test of QED

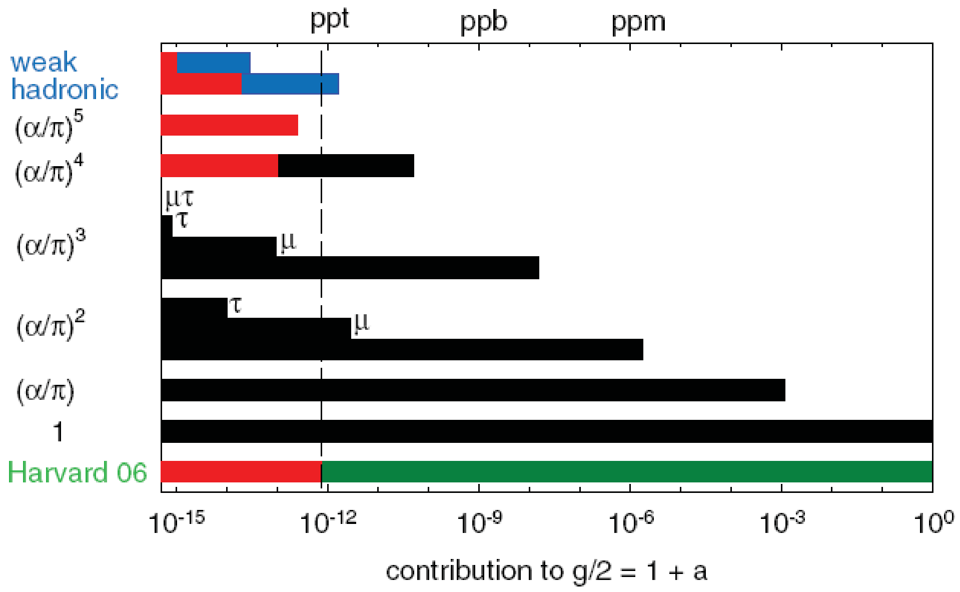


FIG. 2 (color). Contributions to $g/2$ for the experiment (green), terms in the QED series (black), and from short-distance physics (blue). Uncertainties are in red. The μ, τ, and $\mu\tau$ indicate terms dependent on mass ratios m_e/m_μ, m_e/m_τ and the two ratios, m_e/m_μ and m_e/m_τ, respectively.

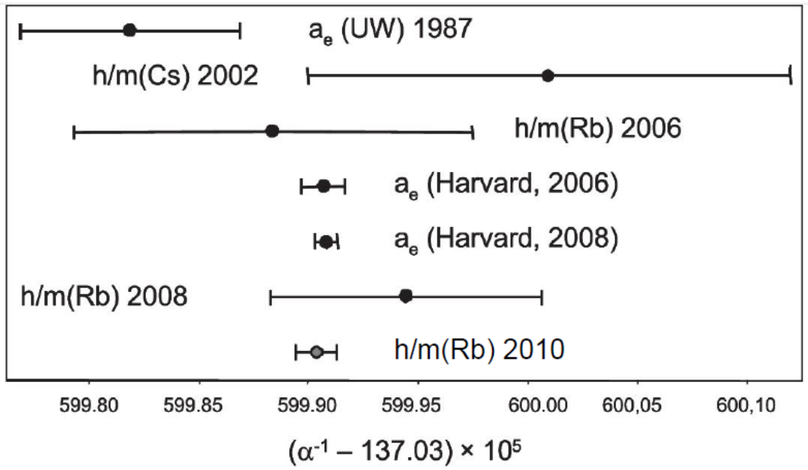
G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom Phys. Rev. Lett. 97, 030802 (2006)

Determination of finestructure constant

- Take measurement and compare to theory to extract finestructure constant

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

$$\alpha^{-1} = 137.035\,999\,710\,(90)\,(33)\,[0.66\ \text{ppb}][0.24\ \text{ppb}], = 137.035\,999\,710\,(96)\,[0.70\ \text{ppb}].$$



- Need for independent measurement of finestructure constant to further test QED
  - Measurement of recoil velocities for Rb (in an optical lattice) or Cs (in an atom interferometer)
  - Currently alpha at order 8 ppb

Developments on the way

20 years

- Resolve lowest cyclotron and spin states
- Quantum jump spectroscopy
- Cavity-controlled spontaneous emission (linewidth reduction)
- Radiation field controlled by cylindrical trap cavity
- Cooling away of blackbody photons
- Synchronized electrons probe cavity radiation modes
- Elimination of nuclear paramagnetism (silver electrodes)
- One-particle self-excited oscillator

Electron and Positron

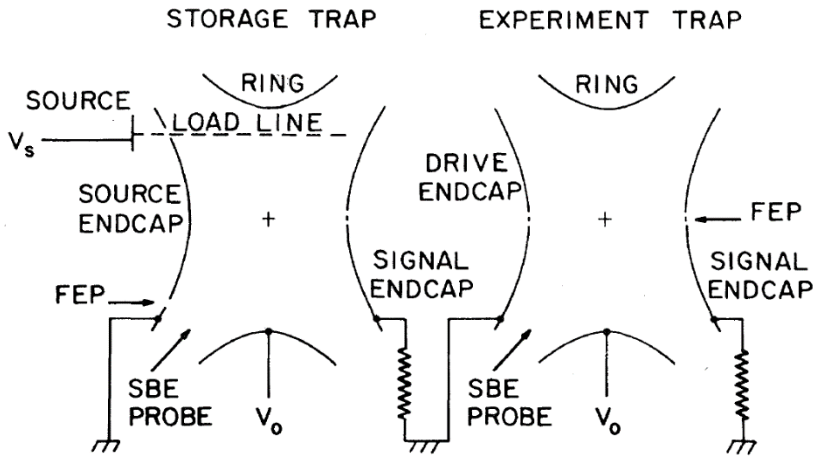
VOLUME 59, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1987

New High-Precision Comparison of Electron and Positron g Factors

Robert S. Van Dyck, Jr., Paul B. Schwinberg, and Hans G. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 23 March 1987)

Single electrons and positrons have been alternately isolated in the same compensated Penning trap in order to form the geonium pseudoatom under nearly identical conditions. For each, the g-factor anomaly is obtained by measurement of both the spin-cyclotron difference frequency and the cyclotron frequency. A search for systematic effects uncovered a small (but common) residual shift due to the cyclotron excitation field. Extrapolation to zero power yields e^+ and e^- g factors with a smaller statistical error and a new particle-antiparticle comparison: $g(e^-)/g(e^+) = 1 + (0.5 \pm 2.1) \times 10^{-12}$.

PACS numbers: 14.60.Cd, 06.30.Lz, 12.20.Fv, 32.30.Bv



P. B. Schwinberg, R. S. Van Dyck, Jr., and H. G. Dehmelt
Phys. Rev. Lett. 47, 1679 (1981)

- Same method used for positron – currently known to 2 ppt
- Best CPT test for leptons $|E^{-}_{0,-1} - E^{+}_{0,1}|/m_0c^2 = |\Delta a|\hbar\omega_c/2m_0c^2 = |3 \pm 12| \times 10^{-22}$
- Redo measurement with positron in improved setup – cavity shift
- Within error bounds no diurnal variations observed

Muon and Antimuon

Electron precisely measured – Why do the Muon/Antimuon?

- Perturbative contributions to magnetic moment scale with mass

$$g = 2(1 + a_\mu) \qquad a_\mu(QED) \propto \left(\frac{m_\mu}{m_e}\right)^2 a_e(QED)$$

a_e(had) = 1,682(20) 10^{-12}
a_e(weak) = 0,0297(5) 10^{-12}

a_μ(had) = 709.6 (7.) 10^{-10}
a_μ(weak) = 15.4 (0.3) 10^{-10}

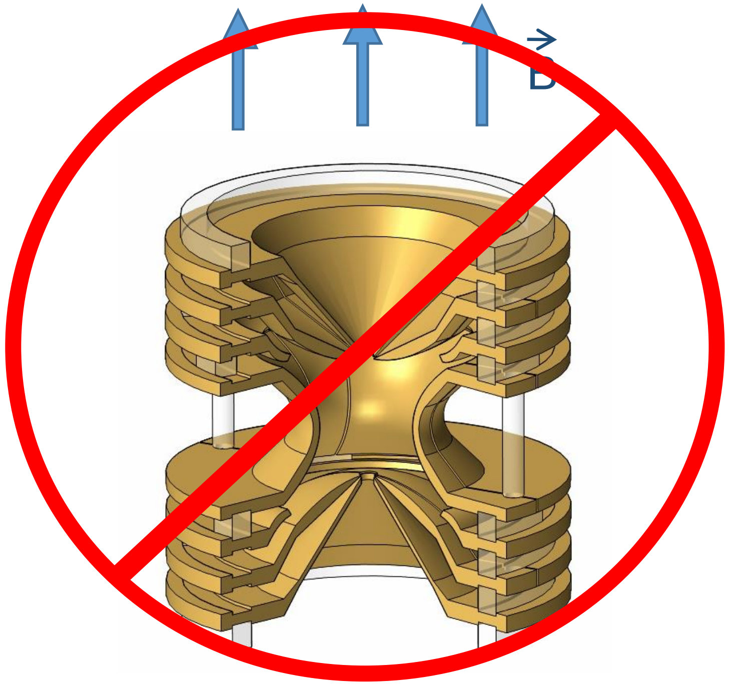
All effects, also beyond SM, are enhanced by a factor of 200^2

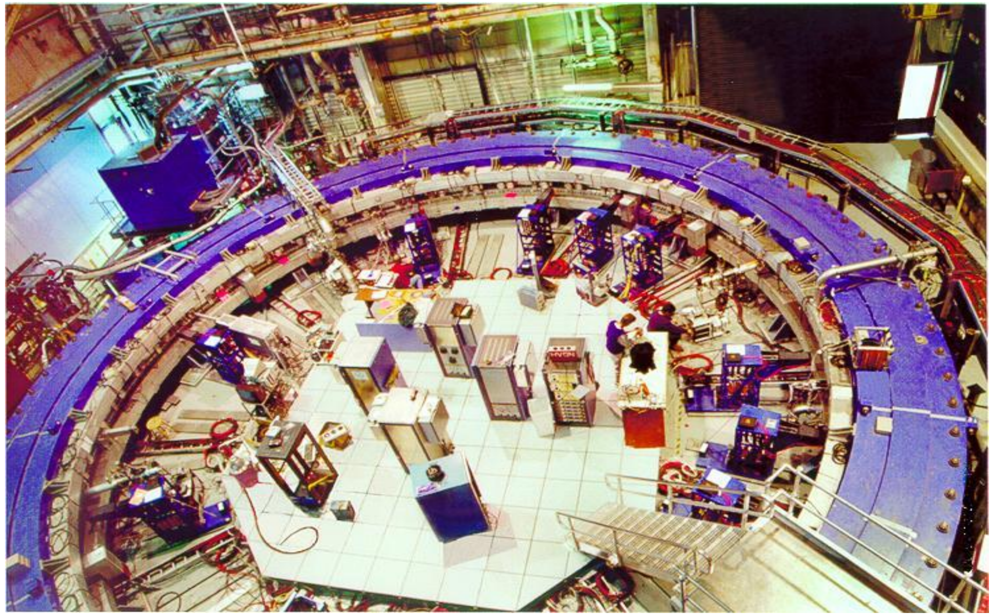
However….

electron lifetime: …..

muon lifetime: 2.20*10^{-6} s

tauon lifetime: 2.96*10^{-13} s





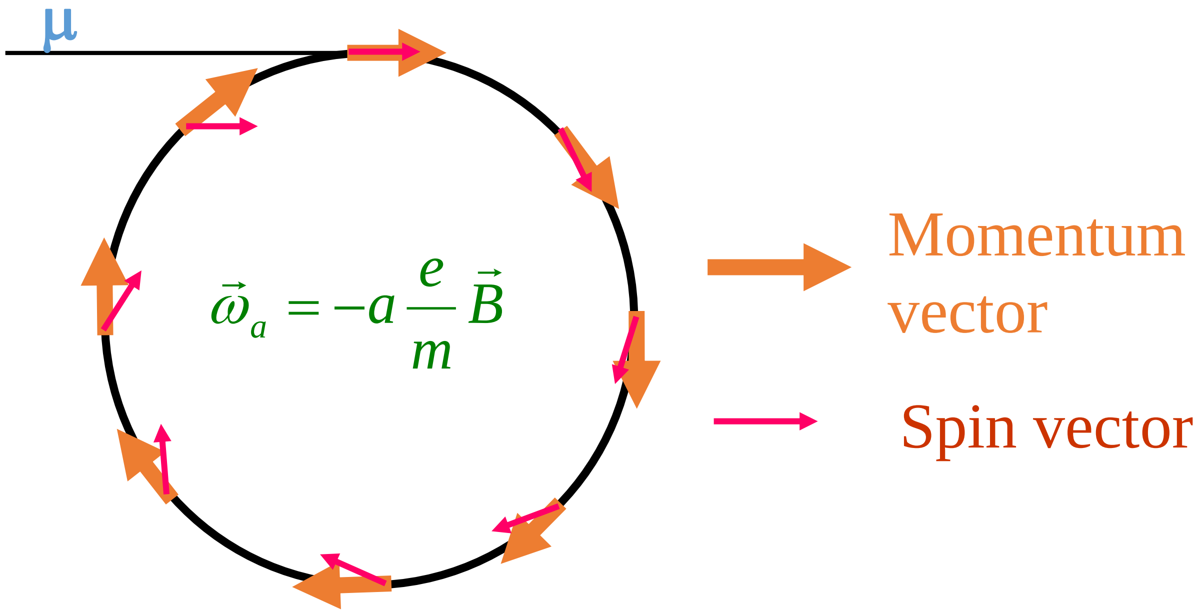
How to measure muon *g*?

- Same principle as for electron

$$\omega_c = \frac{eB}{m}$$

$$\omega_s = \frac{g}{2}\frac{eB}{m}$$

$$\Rightarrow \quad \frac{\omega_s - \omega_c}{\omega_c} = \frac{\omega_a}{\omega_c} = \left(\frac{g-2}{2}\right) = a$$

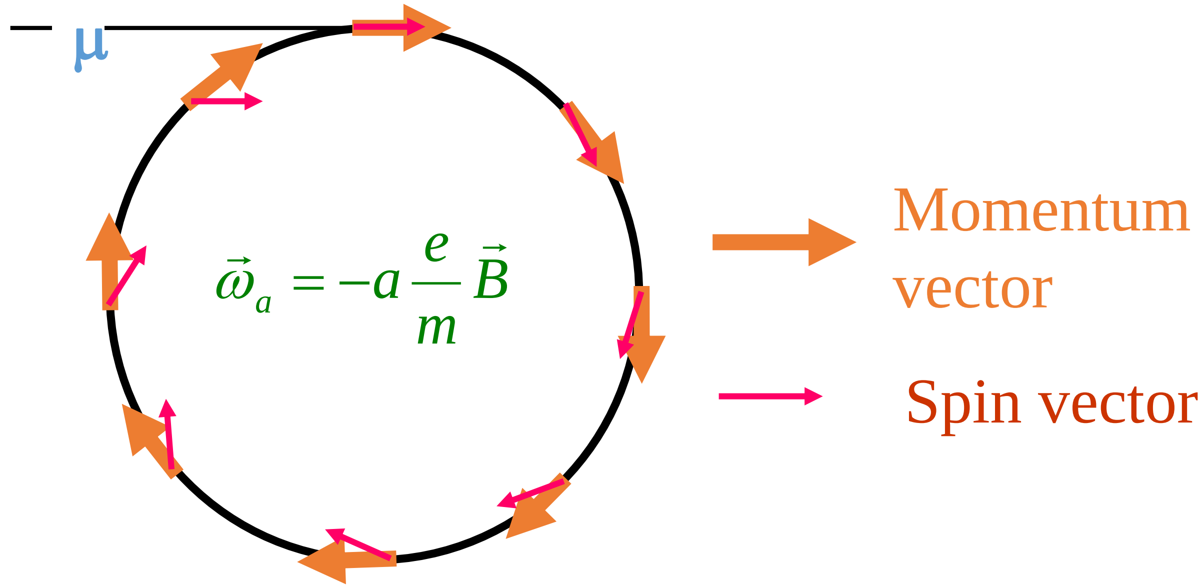


How to measure muon *g*?

- Relativistic particle ?

$$\omega_c = \frac{eB}{m} \qquad \omega_s = \frac{g}{2}\frac{eB}{m}$$

$$\omega_c = \frac{eB}{m}\frac{1}{\gamma} \qquad \omega_s = \frac{g}{2}\frac{eB}{m} + \frac{(1-\gamma)}{\gamma}\frac{eB}{m}$$



Not a problem BUT

However

- Magentic field of storage ring stores only in horizontal plane
- Need vertical focussing to store beam - electrostatic quadrupole fields
- For a relativistic particle this modifies the frequencies

$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right]$$

$$\vec{\omega}_c = \frac{e}{mc}\left[\frac{\vec{B}}{\gamma} - \frac{\gamma}{\gamma^2 - 1}\vec{\beta}\times\vec{E}\right]$$

Operate at specific energy „magic gamma“

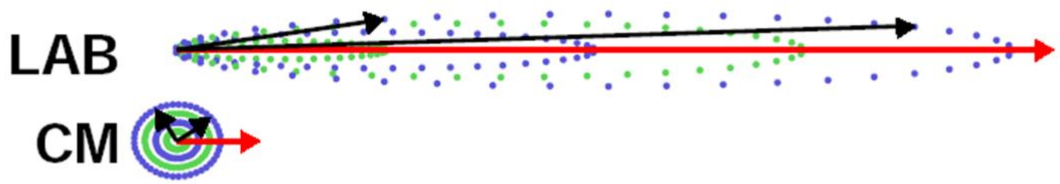
Measure with „external“ B-field sensor

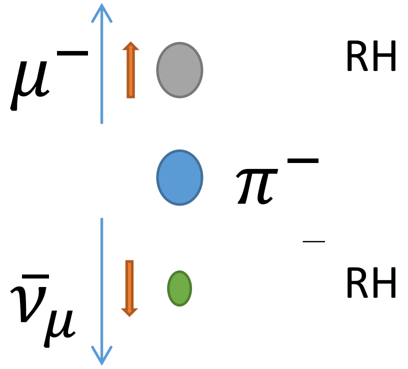
Setup

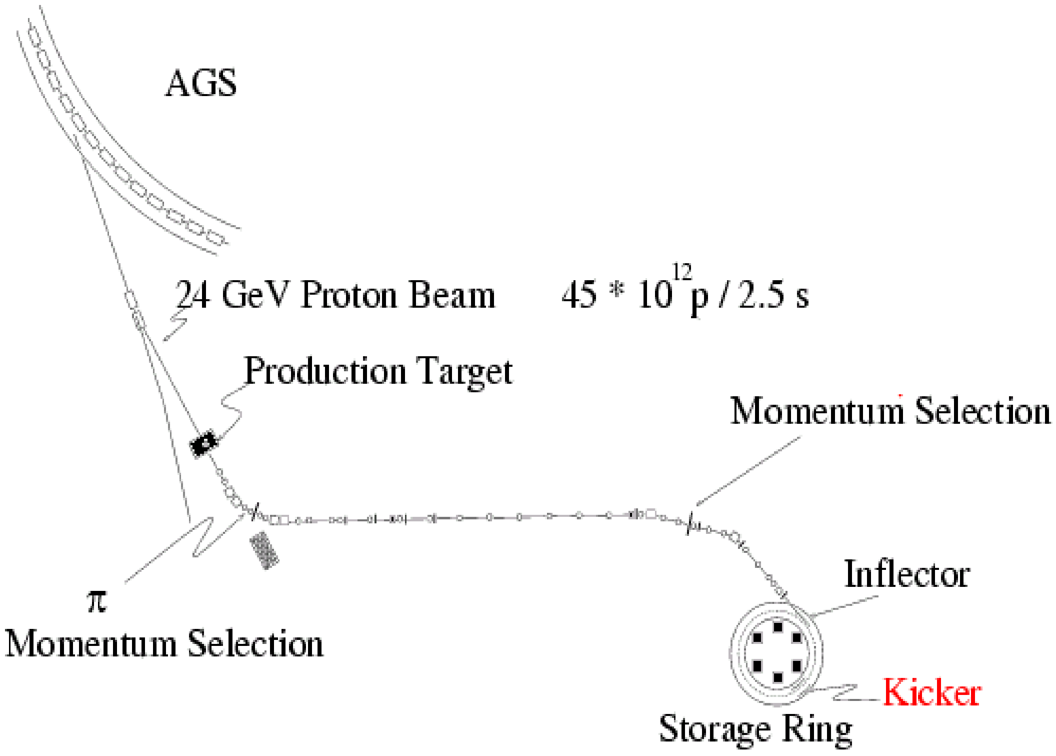
Polarized Muon Source

At Brookhaven in Long Island New York

Make a pion beam, then select high energy muons from parity violating $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ decay



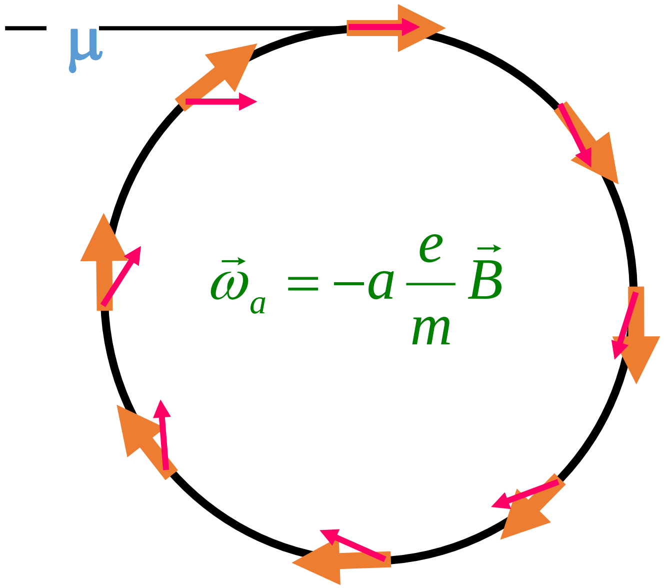




Setup

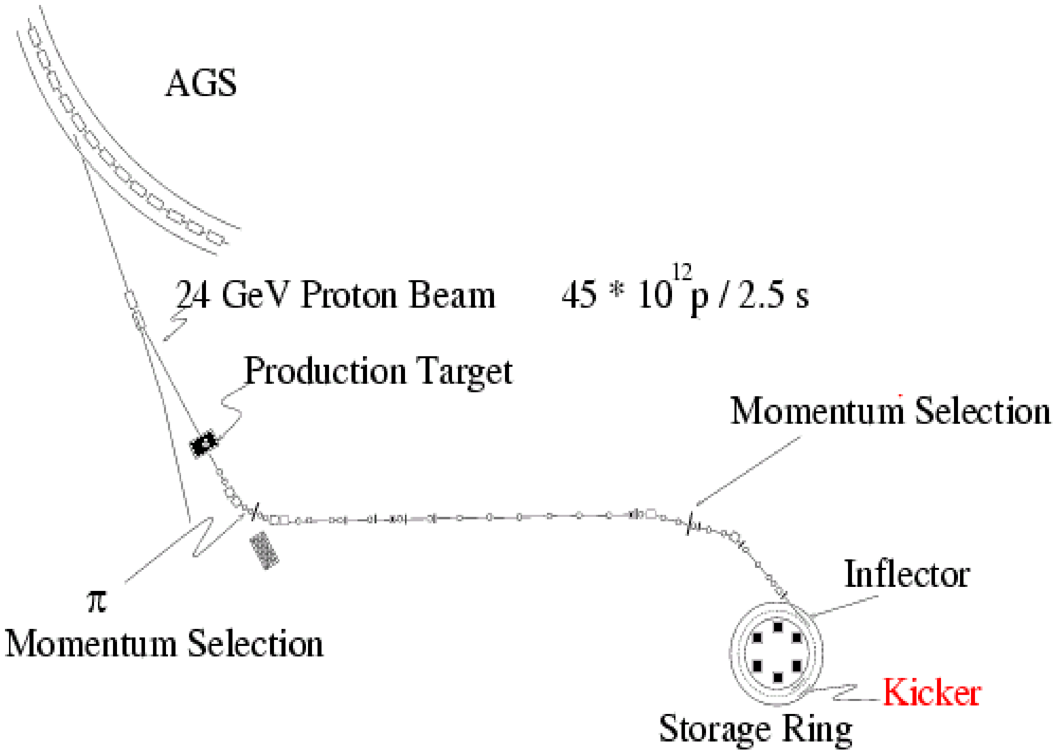
Precession in B-field

Muons to precess through as many cycles as possible



$$\vec{\omega}_a = -a\frac{e}{m}\vec{B}$$

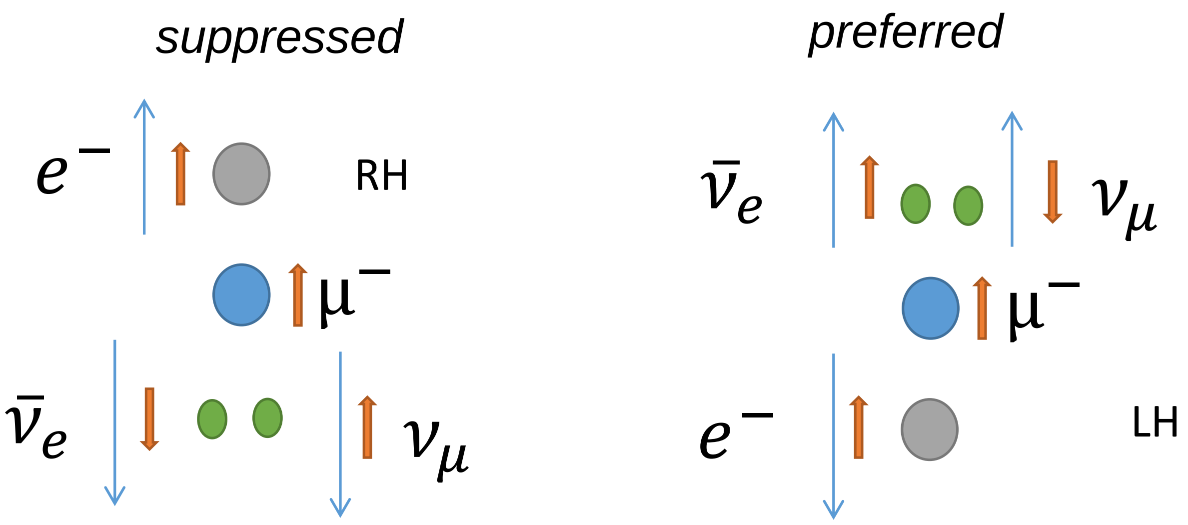
At Brookhaven in Long Island New York



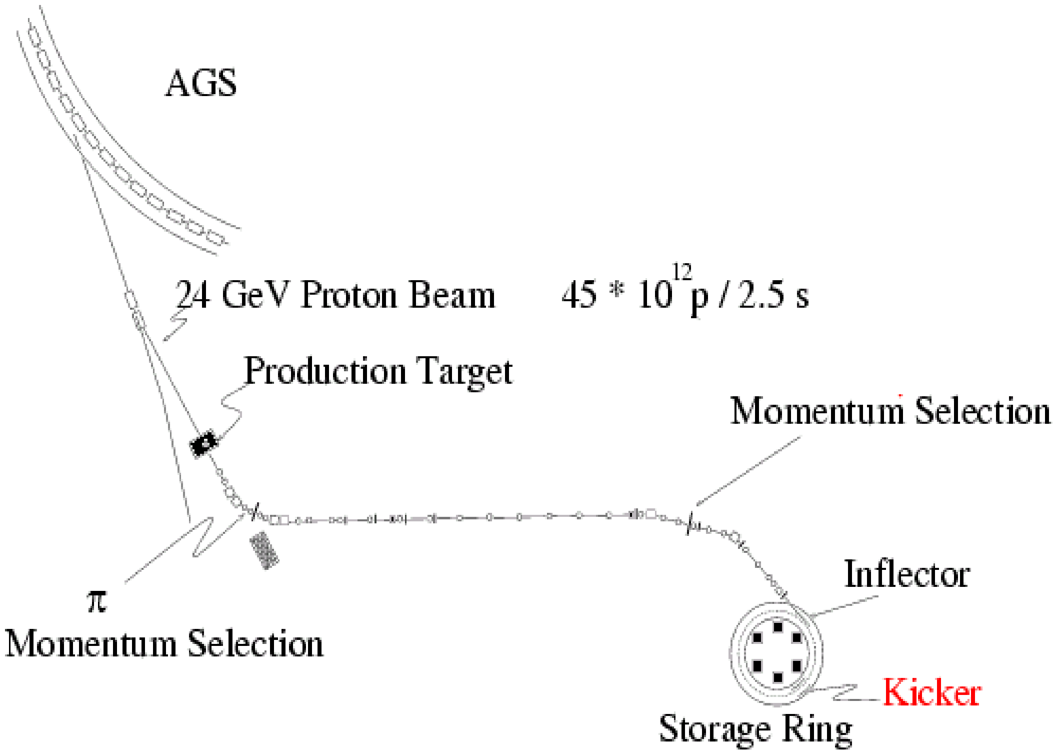
Setup

Detection vs. Time

In parity violating muon decay, $\mu^- \to e^- + \nu_e + \overline{\nu_\mu}$, the high energy *positron is preferentially emitted against the muon spin direction*

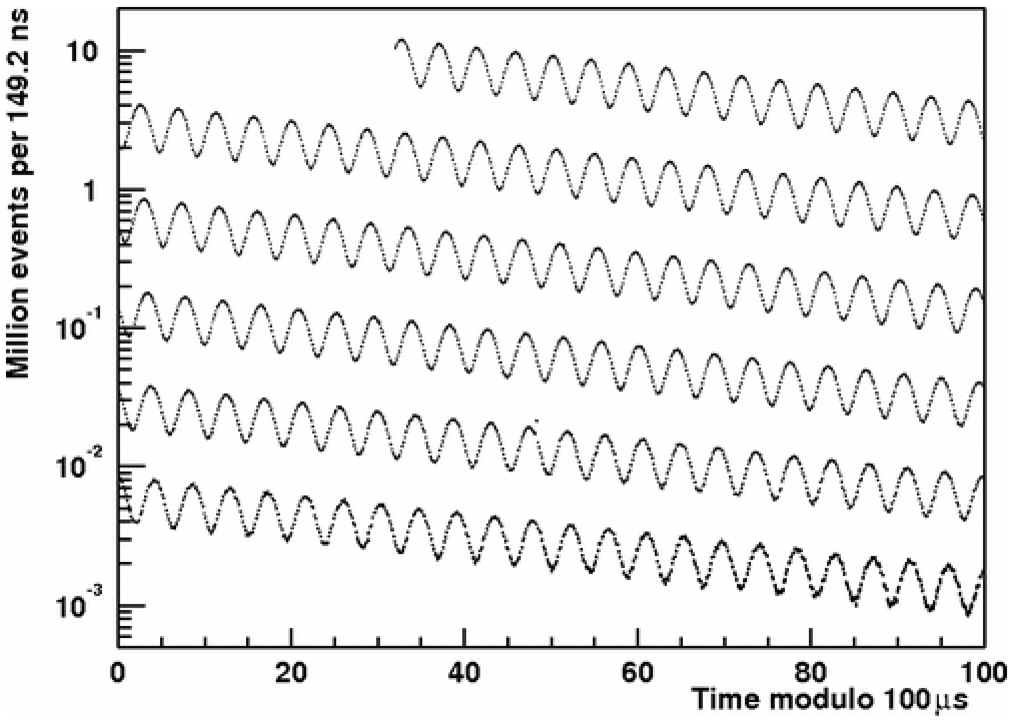


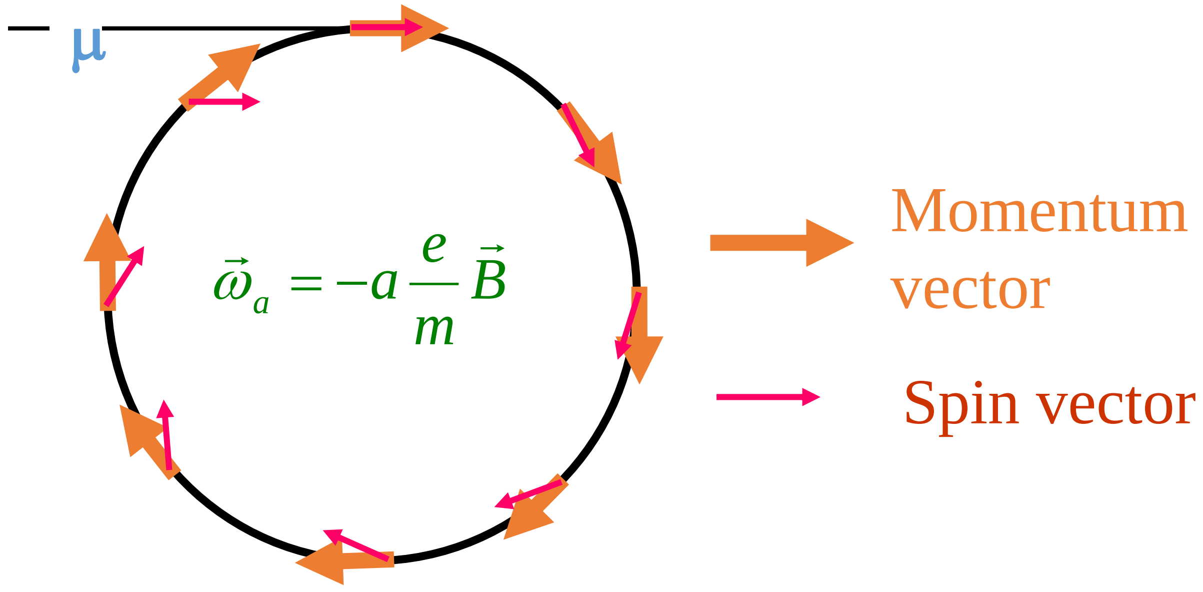
At Brookhaven in Long Island New York



Measurement of Anomalie Frequency

$$N(t) = N_0 e^{-\frac{t}{\gamma\tau}} \left[1 + A\cos(\omega_a t + \phi)\right]$$

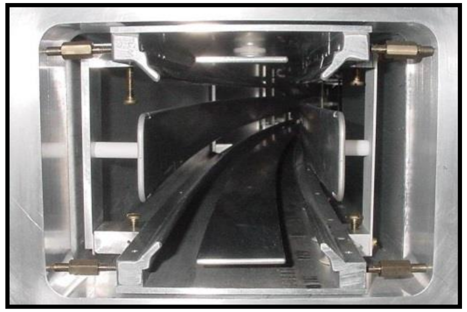


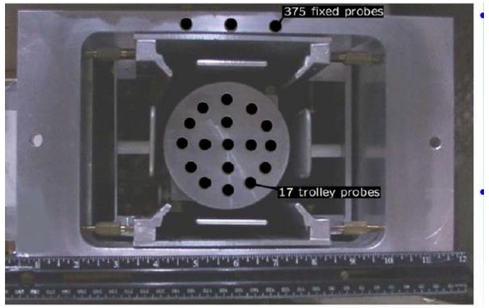


G. W. Bennett *et al.* (Muon g-2 Collaboration) Phys. Rev. D 73, 072003 (2006)

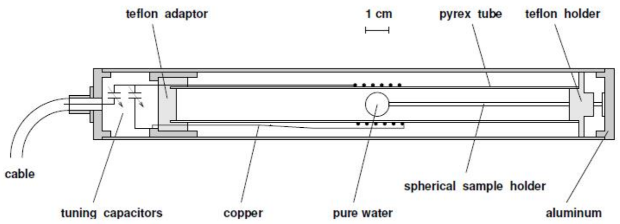
Measurement of Cyclotron Frequency

- Measure magnetic field using array of water NMR probes inside ring





- Relate measured NMR frequencies to absolute standard to determine B-field



(a) Absolute calibration probe


(b) Spherical Pyrex container

$$\omega_{\rm probe} = (1-\delta_t)\omega_p, \text{ where}$$
$$\delta_t = \sigma(\mathrm{H_2O, T}) + \delta_b + \delta_p + \delta_s.$$

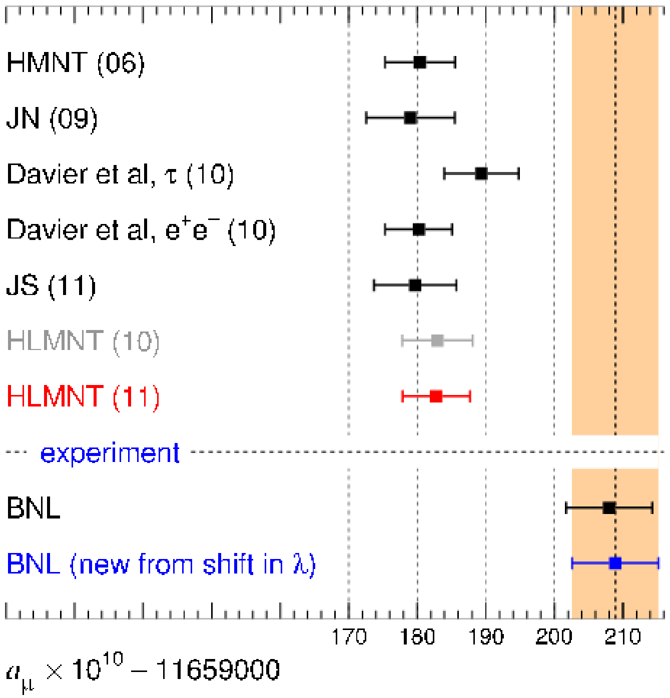
- σ : diamegnetic shielding
- $\delta_{b=}$: bulk suscebility (T-dependent)
- $\delta_{p=}$: paramagnetic inpurities in water
- $\delta_{s=}$: para- and diamagnetism of probe

Muon (g-2) Technical Design Report, arXiv:1501.06858

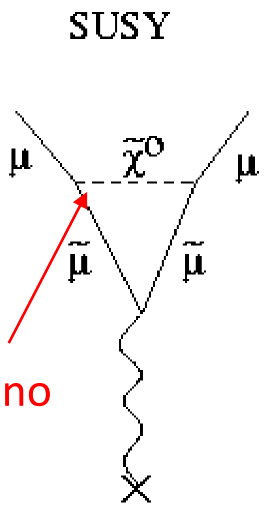
Result

Muon and antimuon are found to agree within 10ppb

But 3.6 Sigma discrepancy observed to theory



Ideas for interpretation



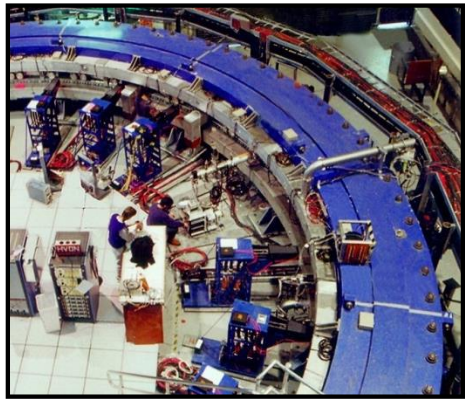
- Superymmetry – every SM particle has partner with same QM numbers exept spin that differs by 1/2

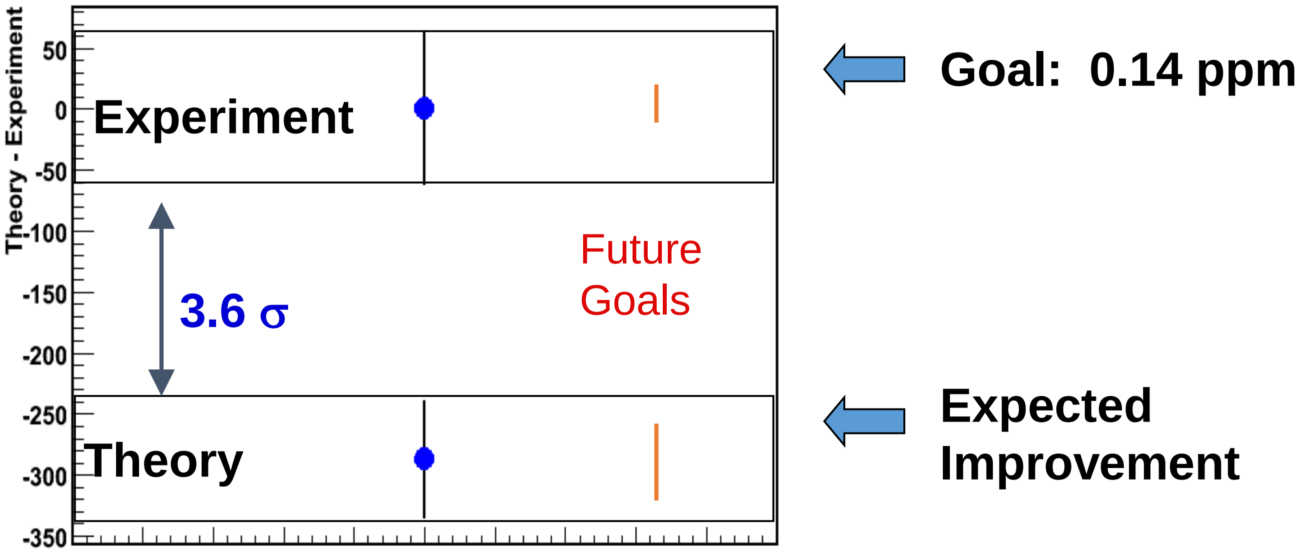
- 5^{th} force mediated by new massive gauge boson (yukawa interaction)

Discrepancy not significant

G. Venanzoni / Nuclear and Particle Physics Proceedings 273–275 (2016) 584–588

Improved measurement palnned at Fermilab





- Higher statistics- precision in anomaly frequency – higher intensity muon beam
- More and improved magnetic field sensors
- Improved accuracy for magnetic field measurement

Proton and Antiproton

Some History: Hydrogen HFS and the proton moment

- First high precision measurement of nuclear magnetic moment - 1972

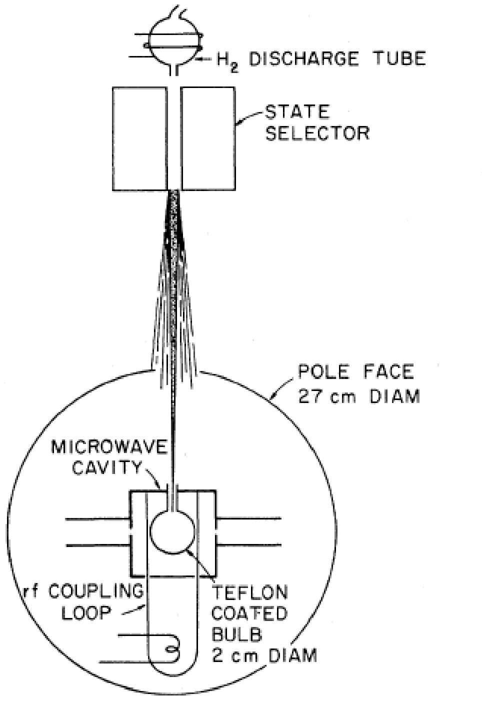


FIG. 9. Schematic diagram of the apparatus.

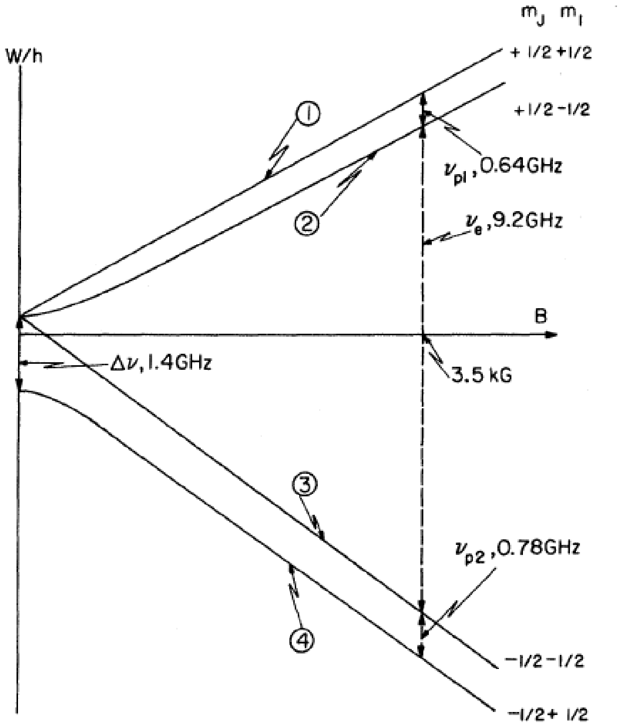


FIG. 1. Energy levels of hydrogen in the ground electronic state in an applied magnetic field.

- Measurement of three transitions
- However four unknowns
- Determination of electron-to-proton magnetic moment ratio "only"

P.F. Winkler, et al. Phys. Rev A 5, 83 (1972)

The proton/antiproton moment in 2012

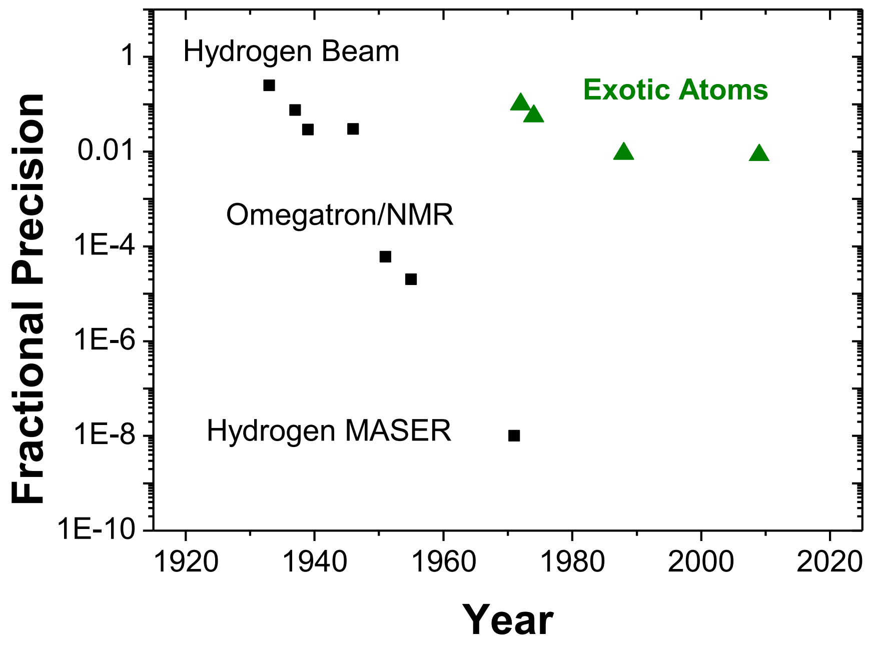
How to deduce proton magnetic moment

0.4ppb ≈ppb 10 ppb

$$g_p = g_e \cdot \frac{m_p}{m_e} \cdot \frac{g_p}{g_p(H)} \cdot \frac{g_e(H)}{g_e} \cdot \boxed{\frac{\mu_p(H)}{\mu_e(H)}}$$

0.78ppt

Requires theoretical corrections at the level of 17.7ppm.



The proton/antiproton moment in 2012

- **Proton**: Hydrogen HFS in magnetic field
  - Issue I: No direct measurement –theory input, which is sougth to be tested
  - Issue II: Difficult to built Antihydrogen Maser

- **Antiproton**: Exotic atom (Antiprotonic Helium) spectroscopy (ASACUSA) with 0.01 precision
  - Issue: Large L-states reduces sensitivety on magnetic moment – lower precision

Perform Measurement in analogy to electron g-2

Proton and Antiproton at BASE

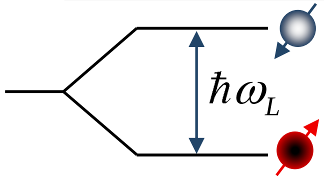
- **Main goal: Measure magnetic moments of the proton and the antiproton with high precision. (factor 1000)**
- Additions:
  - Improvement of proton to antiproton charge-to-mass ratio (factor 10)

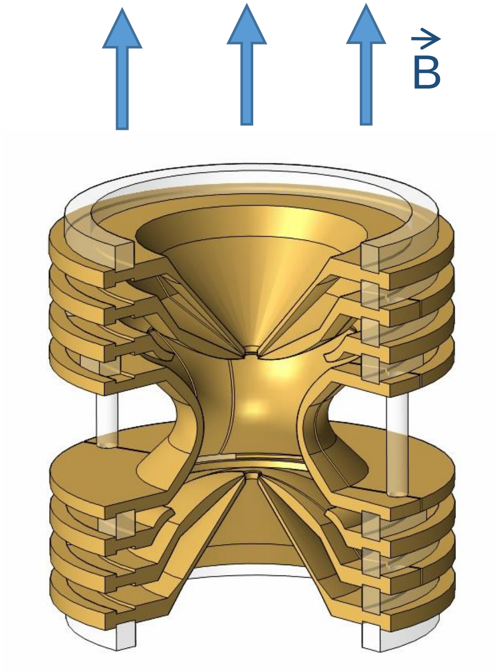
- **BASE-Mainz:** Measurement of the magnetic moment of the proton, implementation of sympathetic cooling of protons
- **BASE-CERN:** Measurement of the magnetic moment of the antiproton
- **BASE-Hannover:** Implementation of quantum logic readout of spin state

Basic Principle for Penning traps

Determination of Larmor frequency in a given magnetic field

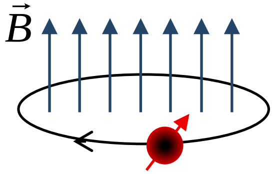
$$\omega_L = g \frac{e}{2m_p} B$$





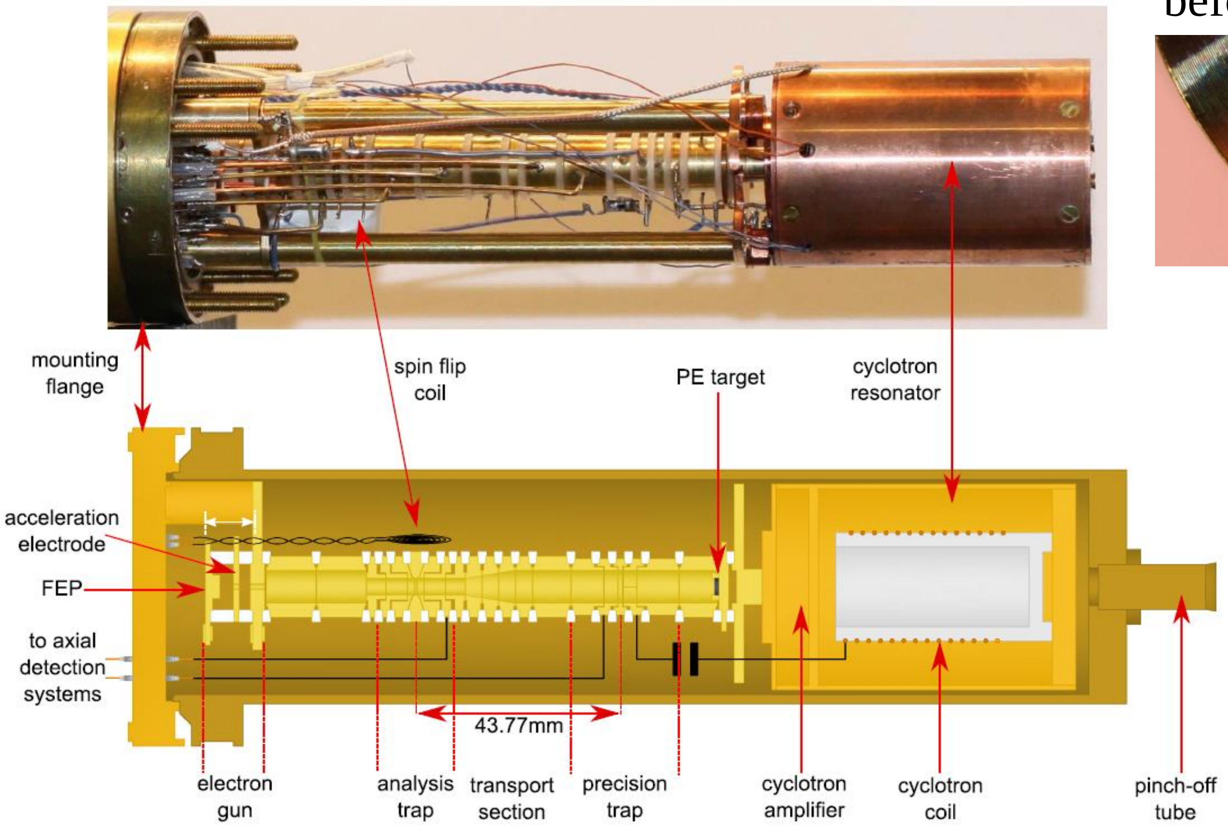
Monitoring magnetic field via simultaneous measurement of the free cyclotron frequency

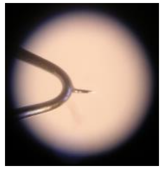
$$\omega_c = \frac{e}{m_p} B$$

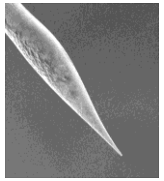


$$g = 2\frac{\omega_L}{\omega_c} = 2\frac{\nu_L}{\nu_c}$$

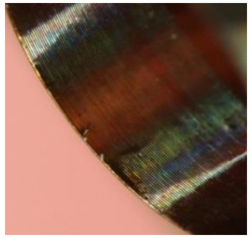
Proton Setup I



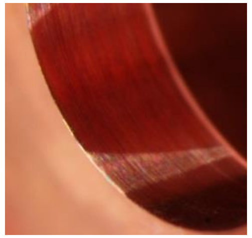




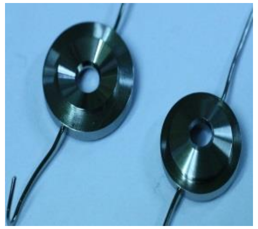
before



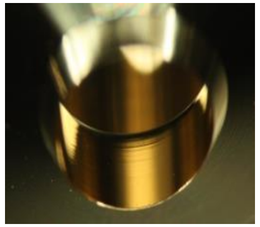
after

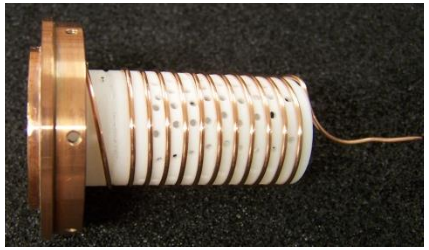


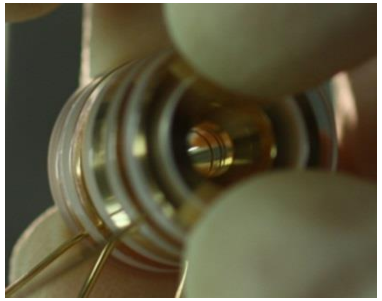
nickel plating



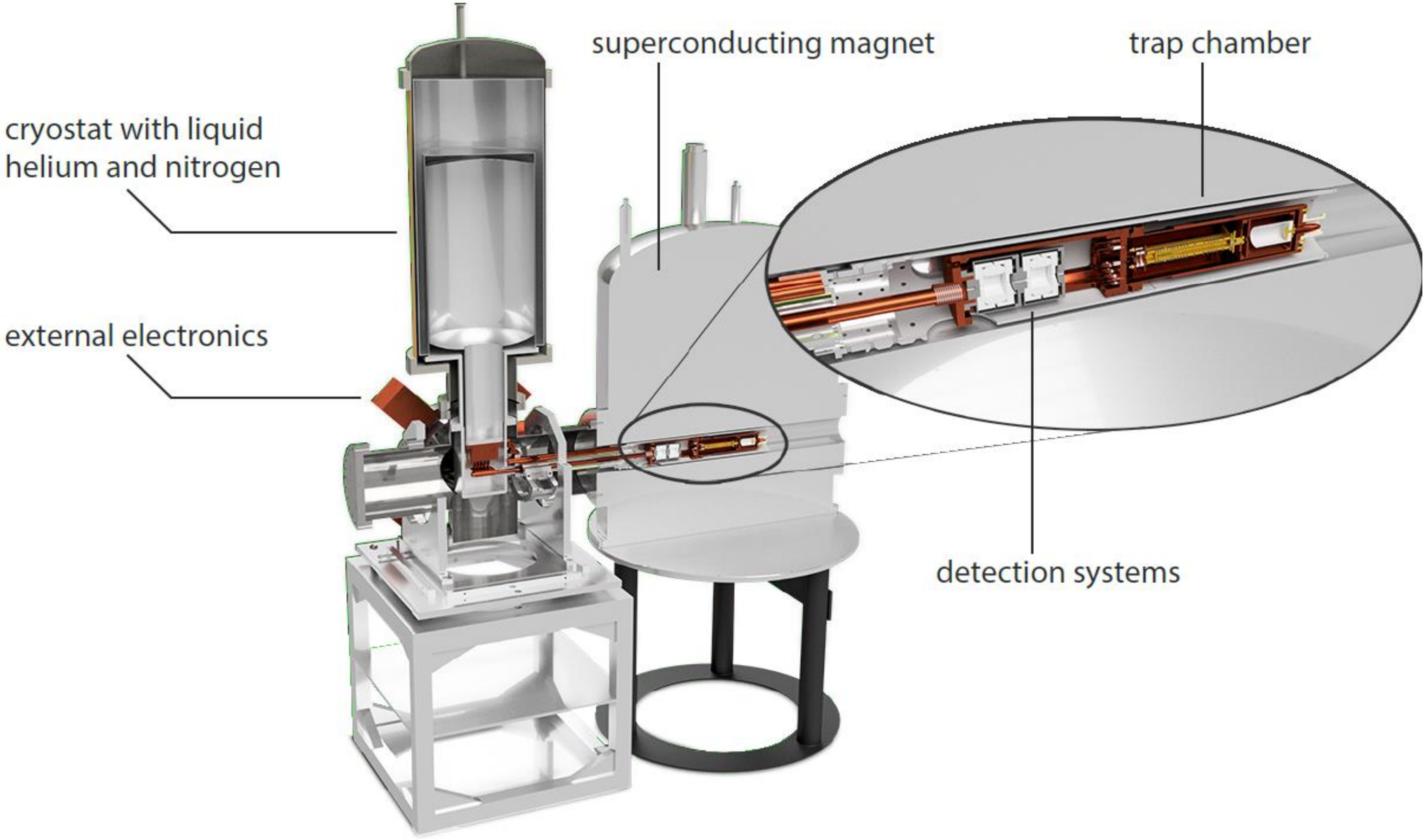
gold plating

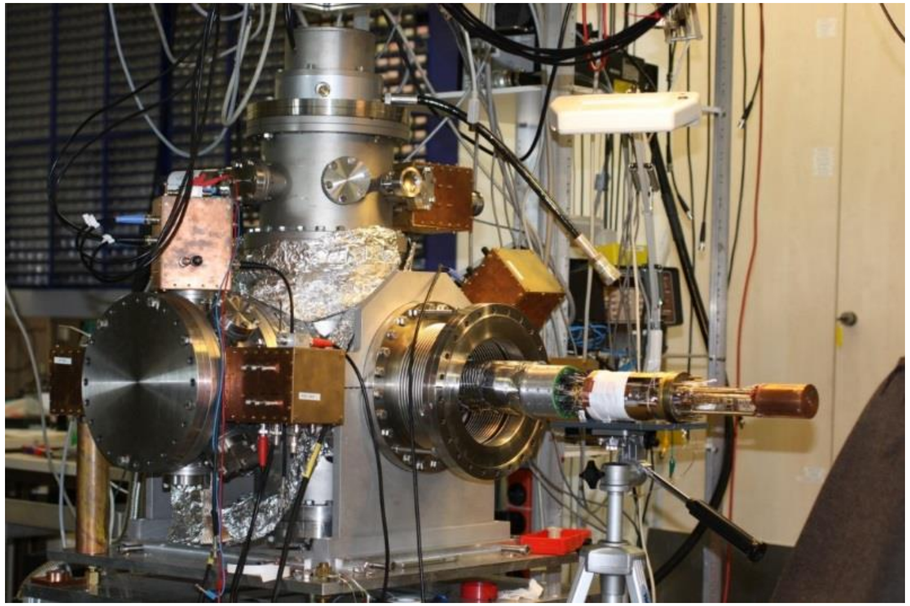






Proton Setup II

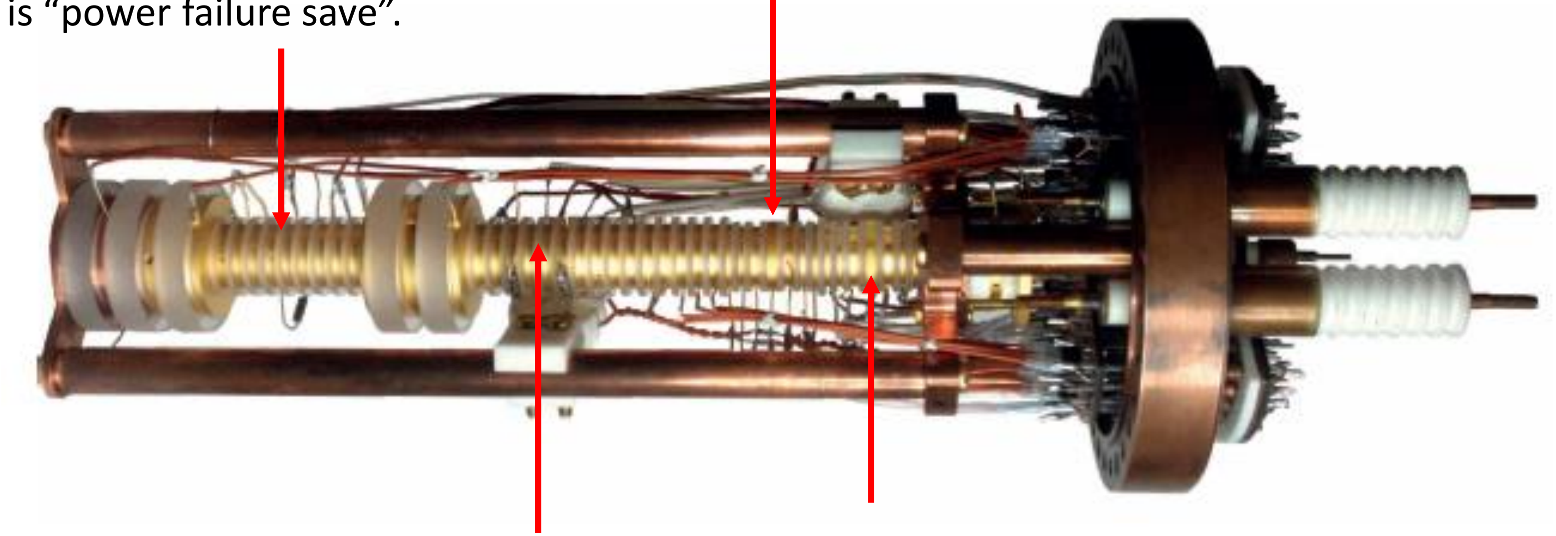




Antiproton Setup

Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
Trap is “power failure save”.

Cooling Trap: Fast cooling of the cyclotron motion, $1/g < 4$ s



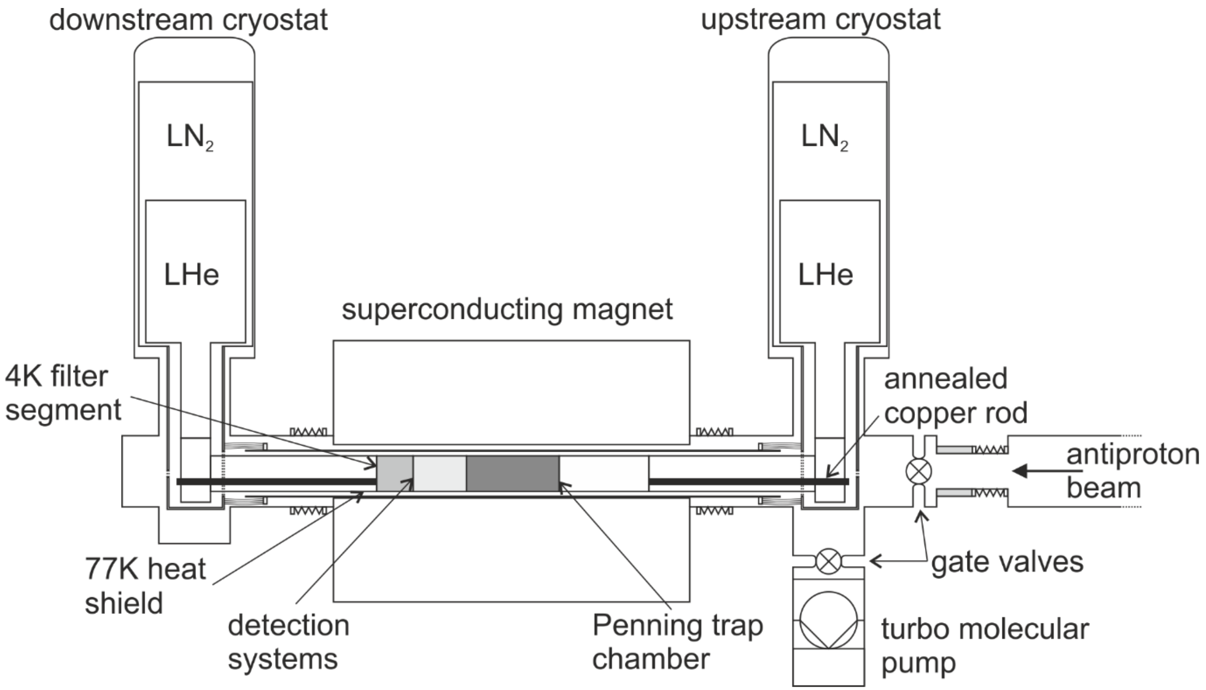
Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5$ mT / mm^2 (10 x improved)

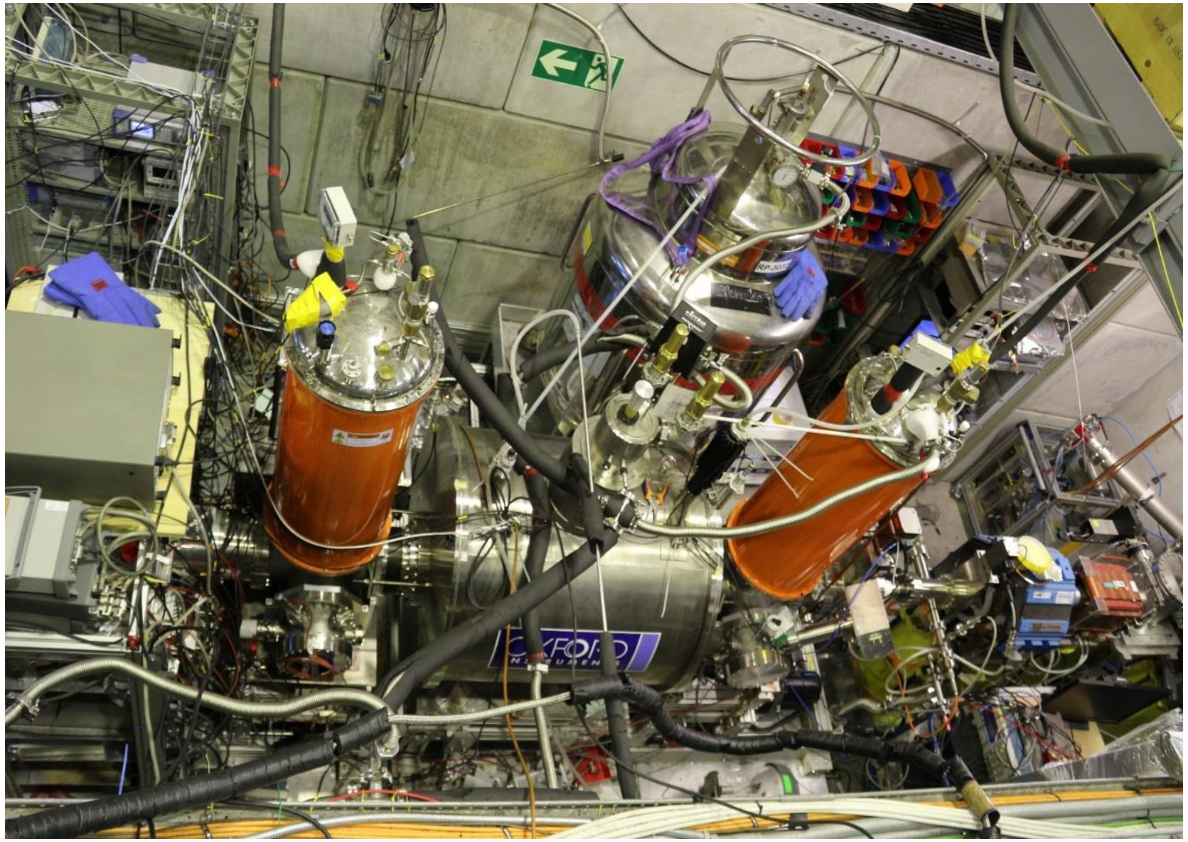
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300$ mT / mm^2

Charge-to-Mass-Ratio measurements

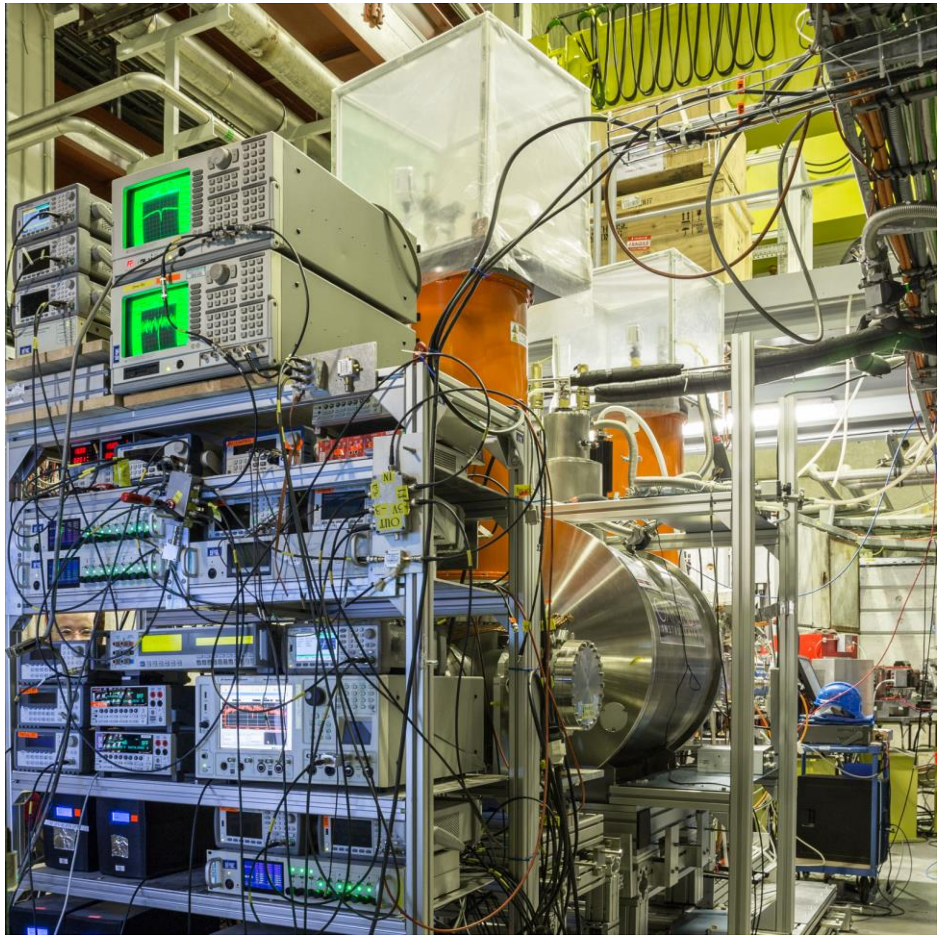
g-factor measurements

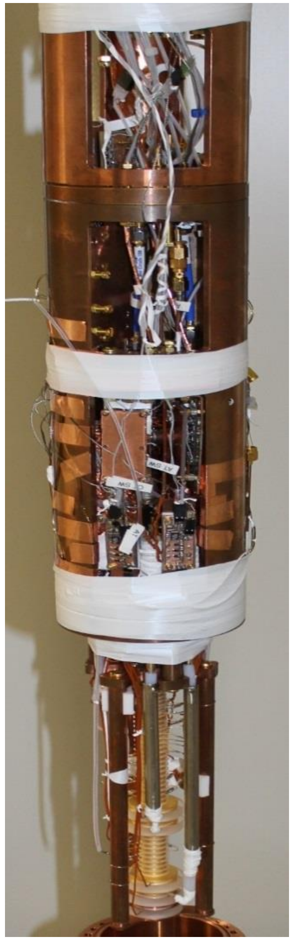
Antiproton Setup

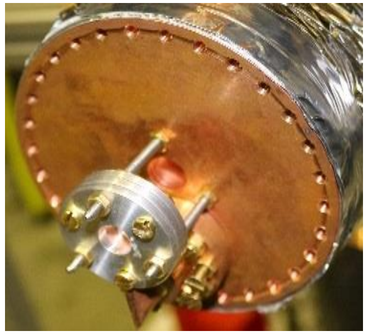


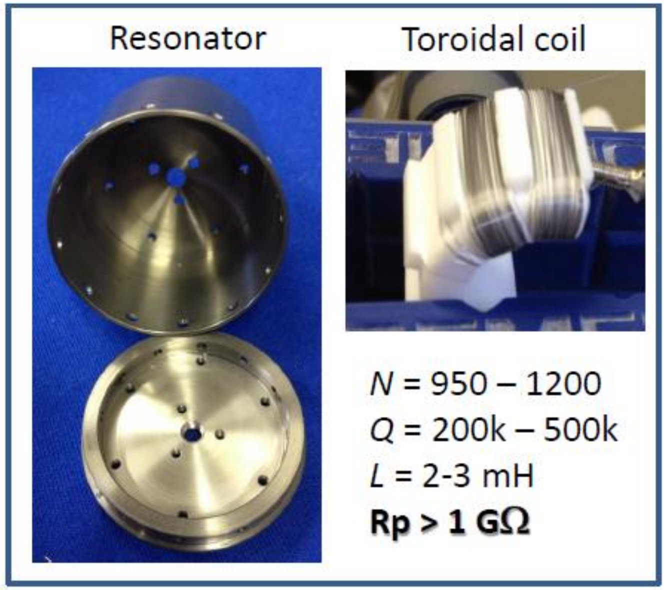


Antiproton Setup

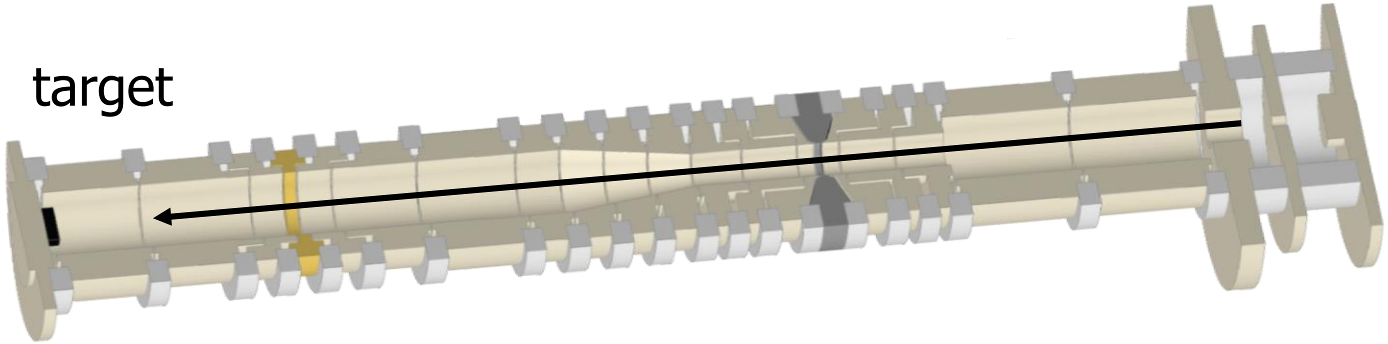




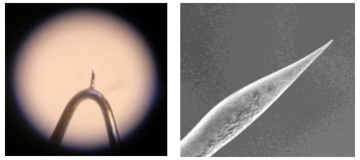




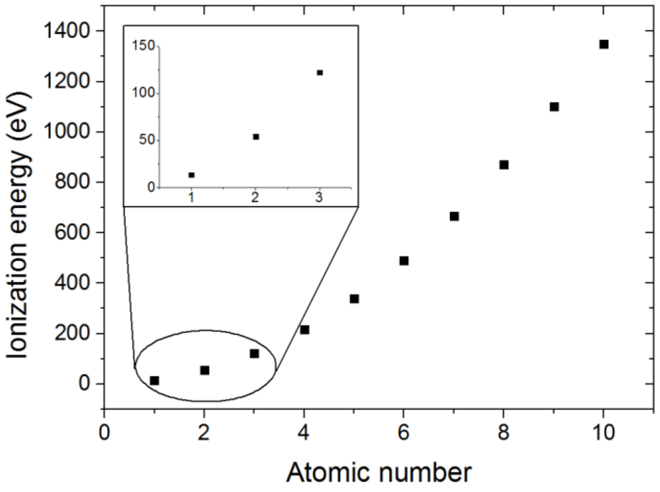
Loading with protons



field emission point

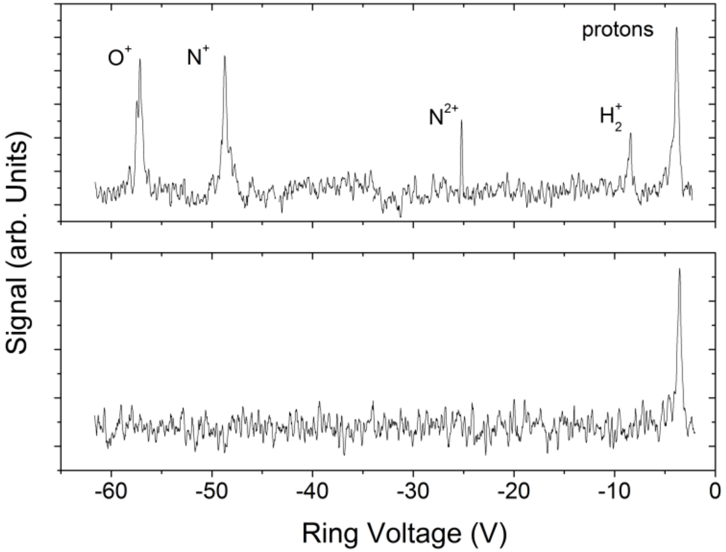


- Only species with q/m of 1 produced are protons



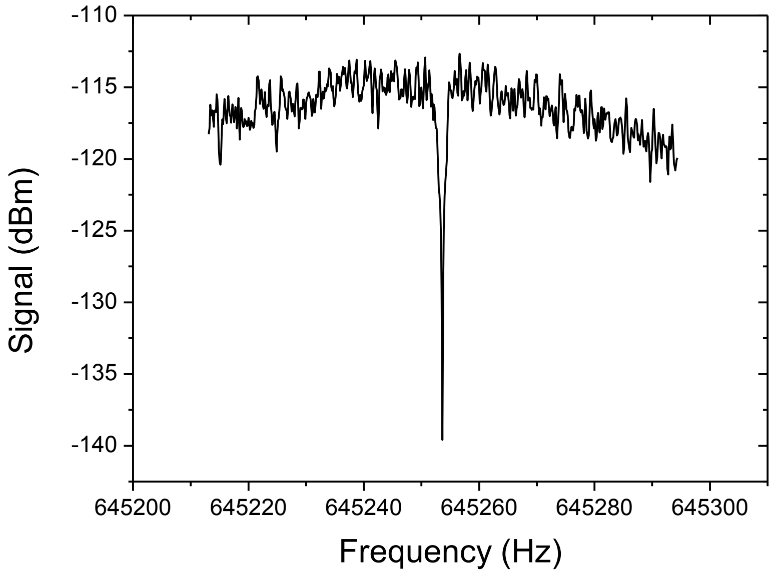
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right)^2 - \frac{\omega_z^2}{2}} \Rightarrow \frac{q}{m} \geq \frac{4C_2U_0}{B_0^2}$$

- Destabilize Magnetron mode – increase trapping voltage



Loading and preperation of antiprotons

- Catching
  - Deceleration of 5.3 MeV antiprotons using degrader foils.
  - Fast HV catching pulses to confine the slow antiprotons up to 5 keV.
- Electron cooling
  - Electron and resistive cooling to 4 K thermal equilibrium energy ~ 320 μeV
- Electron kick-out
- Trap cleaning
- Single particle preparation

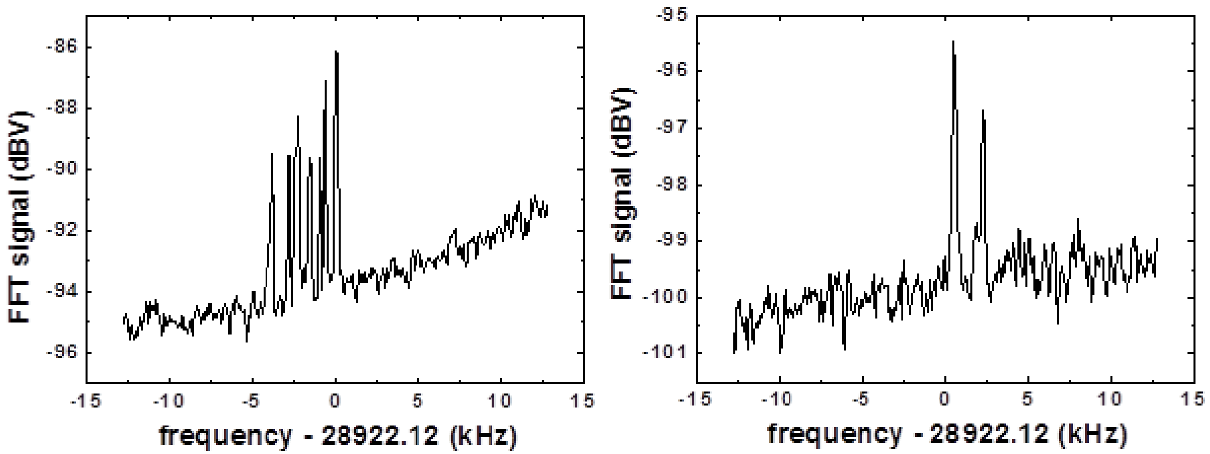


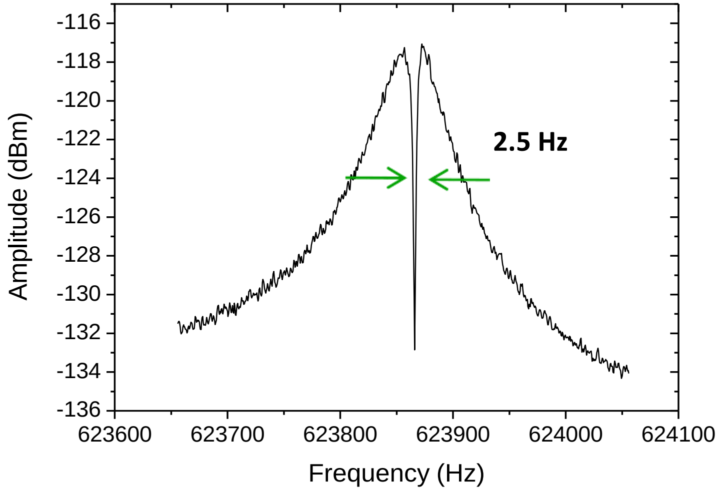
Catching: G. Gabrielse et al, PRL 57, 2504 (1986)
Cooling: G. Gabrielse et al, PRL 63, 1360 (1989)
Measurement: G. Gabrielse et al, PRL 65, 1317 (1990)

How to prepare single particle

Auto-resonant excitation of cyclotron mode for energy selective particle reduction

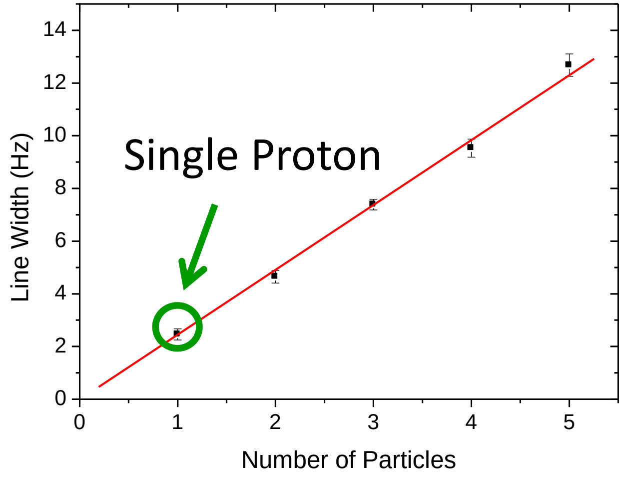
$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$





Linewidth:

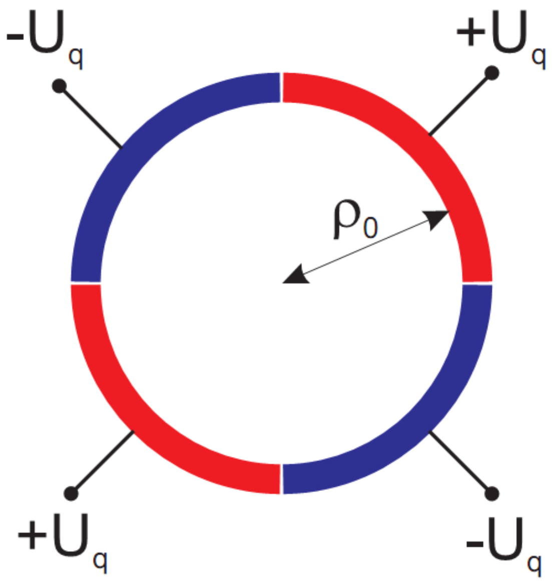
$$\delta\nu_z \propto N_p$$

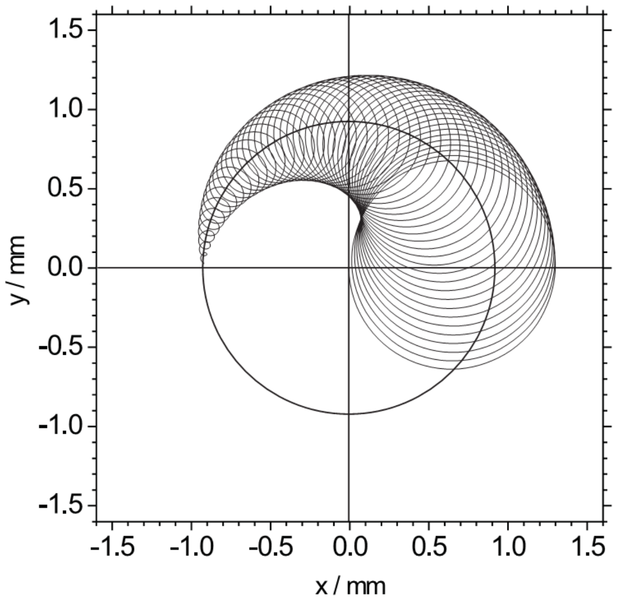


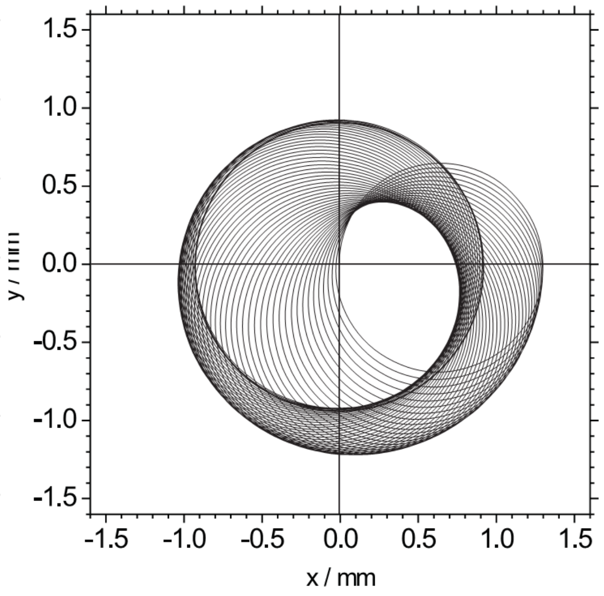
Conversion of Energy

Conversion between two eigenmotions by excitation at the sum frequency:

$$\omega_{rf} = \omega_+ + \omega_-$$



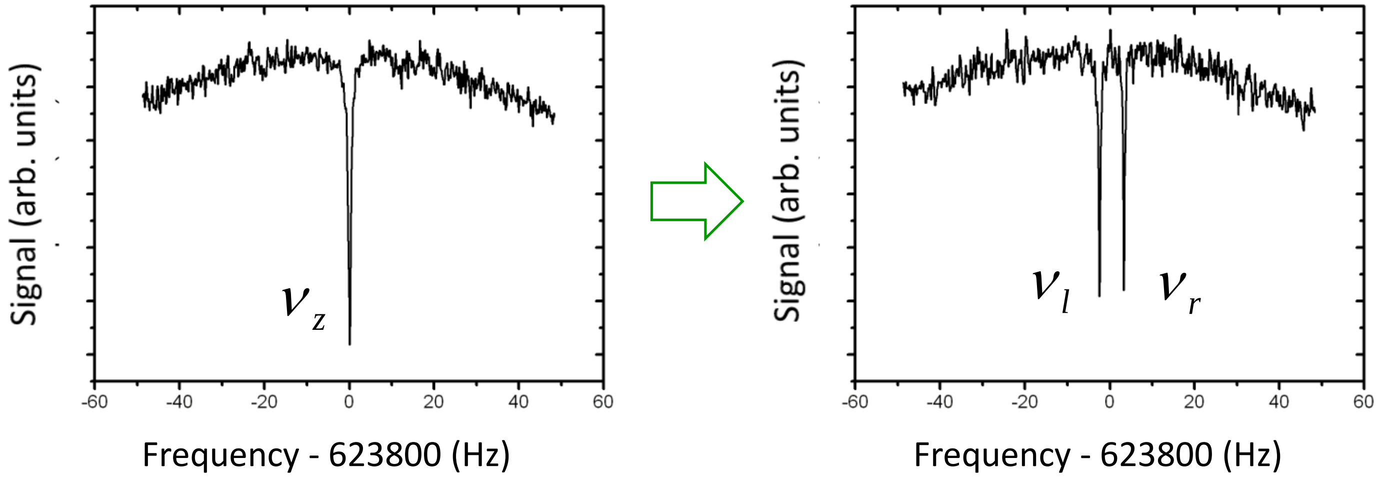




Measurement of radial frequencies

Coupling of modes via rf-sideband coupling, e.g. $\nu_{rf} = \nu_+ - \nu_z$

Amplitude modulation of the axial motion



$$\nu_+ = \nu_{rf} + \nu_l + \nu_r - \nu_z$$

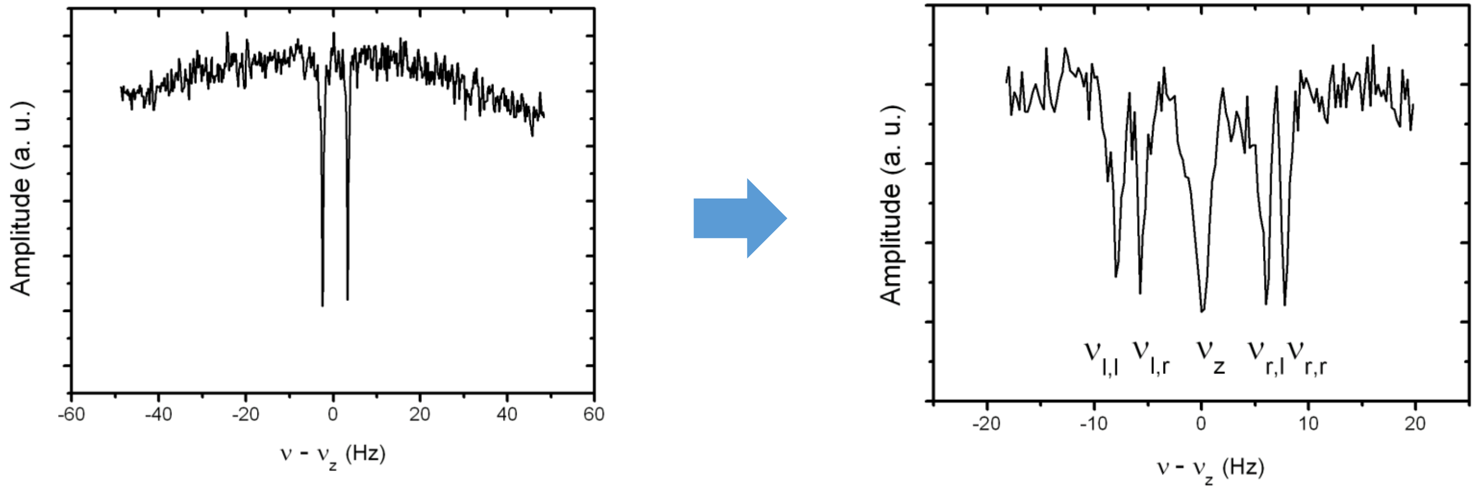
$$\nu_- = \nu_{rf} - \nu_l - \nu_r + \nu_z$$

$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2 \longrightarrow \frac{\Delta \nu_c}{\nu_c} \approx 10^{-9}$$

Measurement of radial frequencies

Additional coupling of remaining mode by frequency modulated drive

Five signals by one single particle



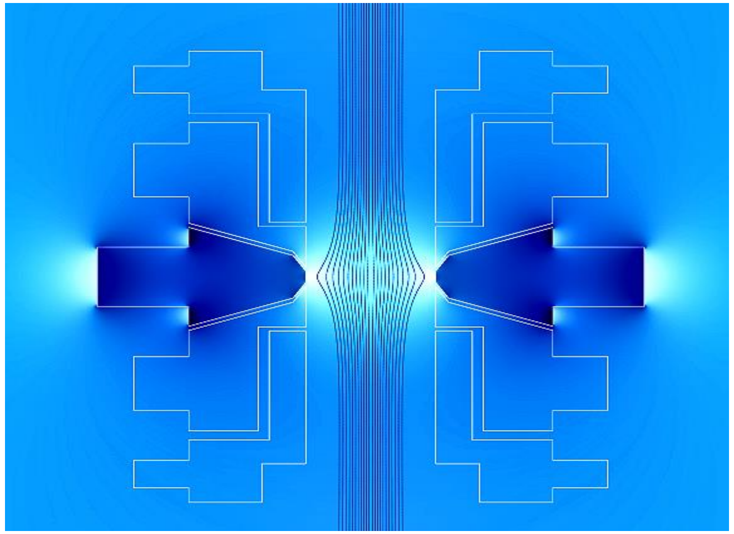
All three eigenfrequencies measured in one shot!

First direct measurement of the free cyclotron frequency at $5*10^{-9}$

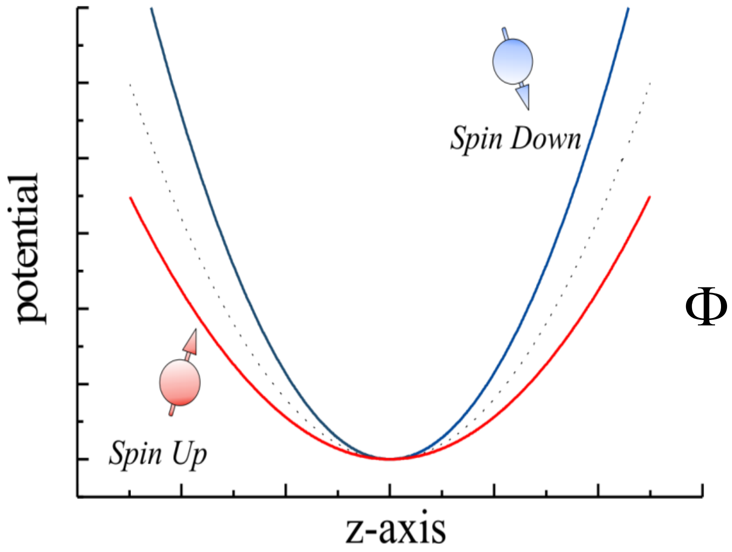
S. Ulmer, K. Blaum, H. Kracke, A. Mooser, W. Quint, C. C. Rodegheri, J. Walz, Phys. Rev. Lett **107**, 103002 (2011)

Spin state detection

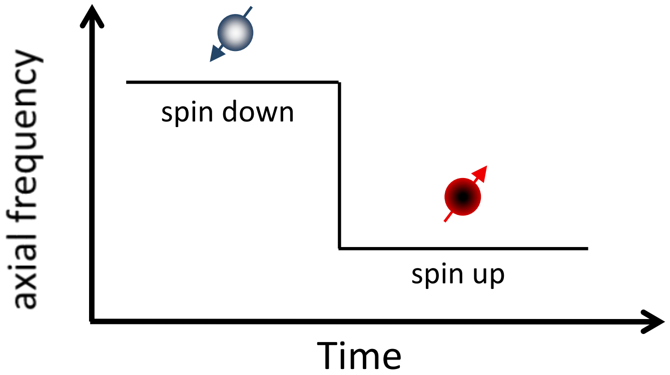
Introduce magnetic inhomogeneity, the magnetic bottle



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



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



Spin flip results in shift of the axial frequency

$$\nu_z \propto \frac{\mu_p}{m} B_2$$

Spin State Detection – Challange I

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

Dealing with nuclear magneton requires huge magnetic bottle of

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

to obtain frequency jump due to spin transition of

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

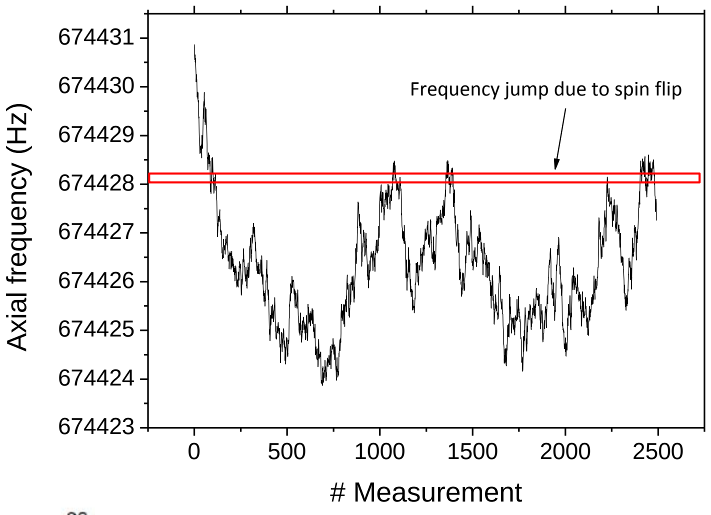
<u>BUT</u>

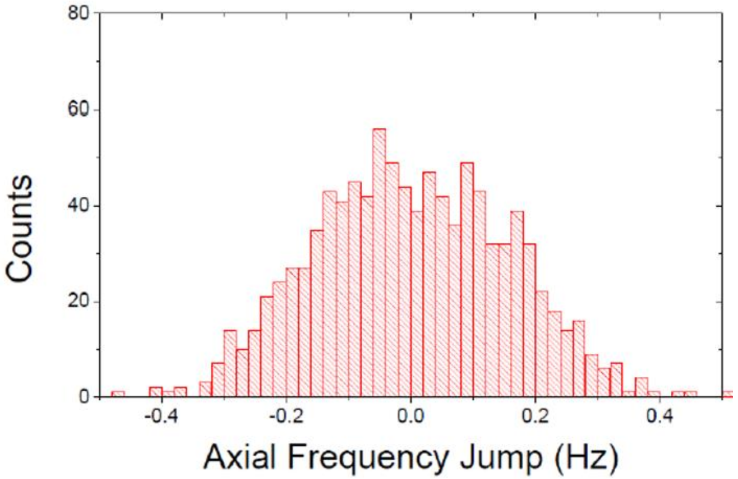
$$\nu_z \propto + \frac{1}{2\pi \nu_{z,0}} \frac{B_2}{B_0} E_{radial}$$ radial angular momentum

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

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

Spin State Detection – Challange II





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

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

Ξ = 150mHz - not stable enough for observation individual spin transition

Axial frequency fluctuation Ξ increases due to frequency jump caused by spin transitions

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

Measure Ξ_{SF} and $\Xi_{ref} \rightarrow$ obtain SF-Probability!!!

Detecting spin transitions in a statistical measurement!

Statistical Detection of Spin Flips

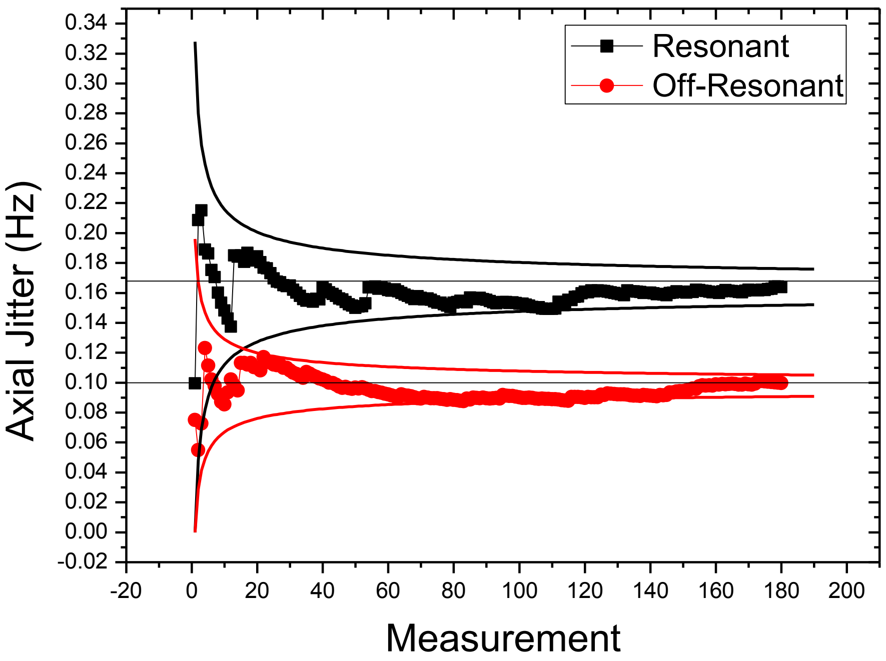
Measure axial frequency stability:

1.) reference measurement with detuned drive on,

2.) measurement with resonant drive on.

Spin flips add up

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



Cumulative measurement:

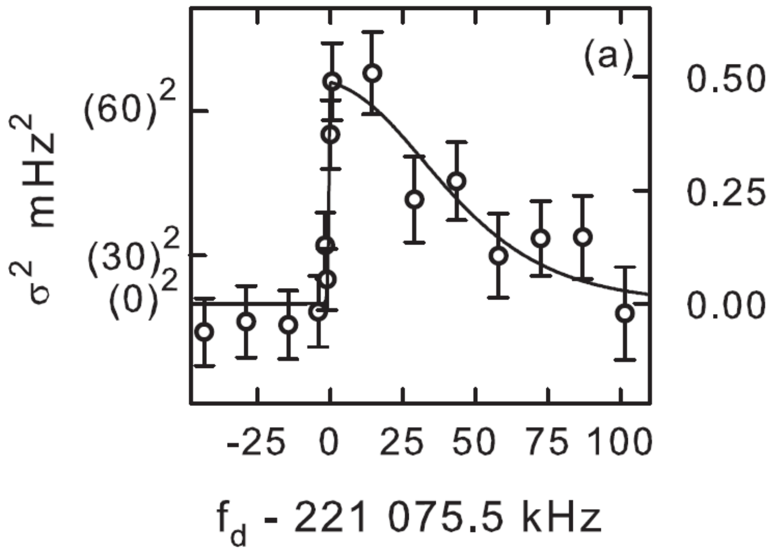
Black – frequency stability with superimposed spin flips.

Red – background stability

First Single Proton/Antiproton Measurements

Antiproton

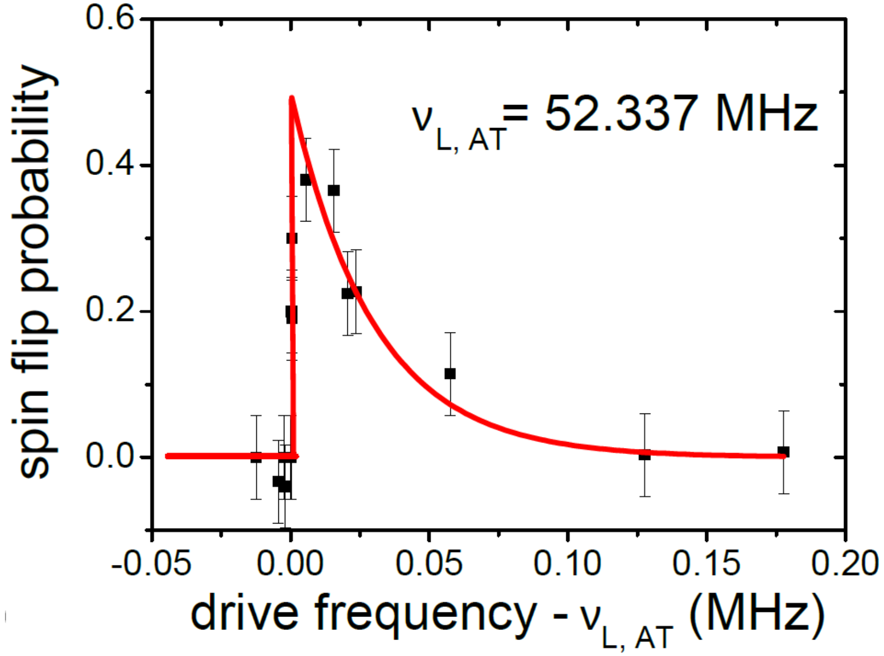
Harvard 2013



J. DiSciacca et al., Phys. Rev. Lett 110, 130801(2013).

Relative Uncertainty 4.4 ppm

BASE 2017



H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

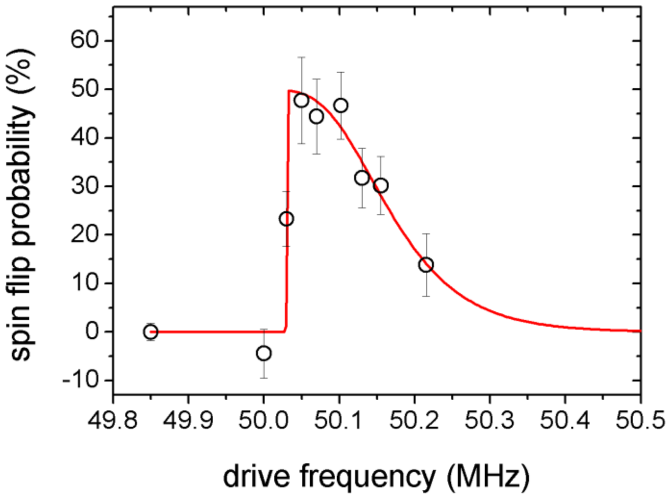
Relative Uncertainty 0.8 ppm

First Single Proton/Antiproton Measurements

Proton

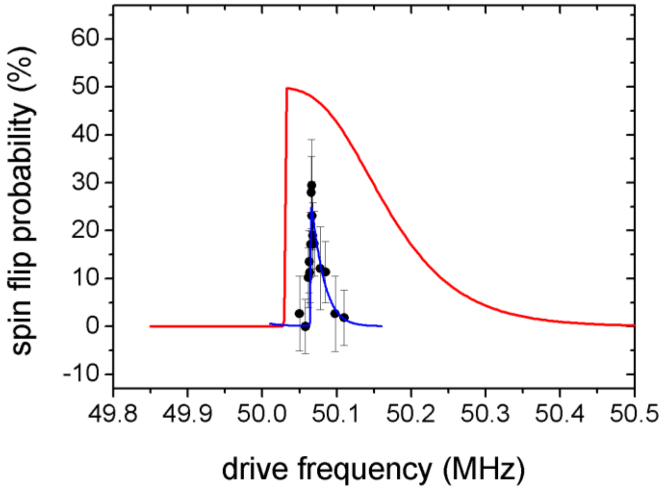
relative precision of 10^{-4}

S. Ulmer et al., Phys. Rev. Lett **106**, 253001 (2011)



reduction of line broadening using feedback cooling

C. C. Rodegheri et al., *New J. Phys.* **14** 063011 (2012)



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

g = 5.585 696 (50)

Limited by magnetic field inhomogeneity

Lineshape in magnetic bottle

The frequencies of interest depend strongly on the particle amplitudes

The axial detector acts as a thermal bath (correlation time 33 ms).

To obtain the g-factor we need to extract the frequencies at zero axial amplitude and identical magnetron radius

$$\frac{g}{2} = \frac{\omega_L(E_z = 0,\ \rho_- = r)}{\omega_c(E_z = 0,\ \rho_- = r)}$$

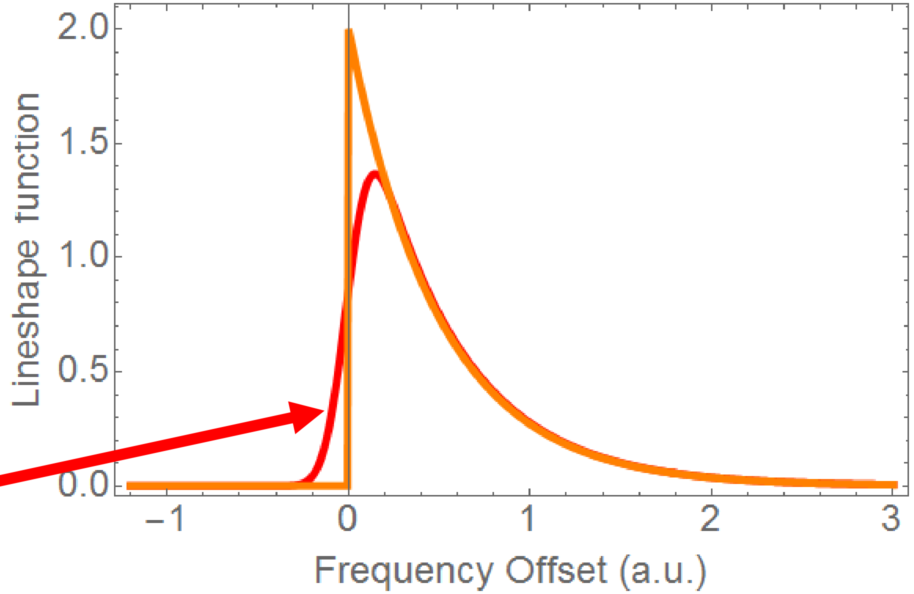
$$\begin{pmatrix} \Delta\nu_+ \\ \Delta\nu_L \end{pmatrix} = \begin{pmatrix} -2.5\,\mathrm{Hz/K} & 1.9\,\mathrm{kHz/K} & -3.8\,\mathrm{kHz/K} \\ -7\,\mathrm{Hz/K} & 5.3\,\mathrm{kHz/K} & -10.7\,\mathrm{kHz/K} \end{pmatrix} \begin{pmatrix} T_+ \\ T_z \\ T_- \end{pmatrix}$$

No concern for 10^{-6} precision

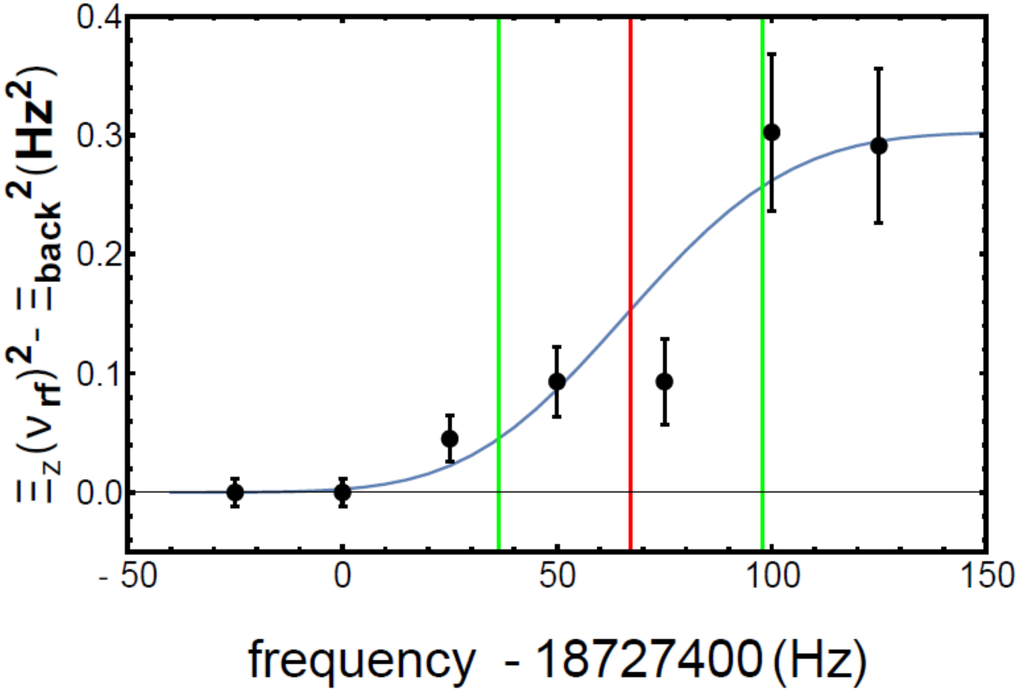
Lineshape reflects the Boltzmann distribution of axial energy

Energy fluctuation smears out the “cut” $E_z = 0$.

Stability requirement 5 mK / 12 h.



Lineshape in magnetic bottle



- Record frequency fluctuations for drive frequencies close to the cut frequency
- The time fraction the drive frequency is above the cut frequency increases the fluctuation
- Energy fluctuations smear out cut frequency
- Cyclotron frequency measurements up to **0.6 ppm precision**

H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

How to improve?

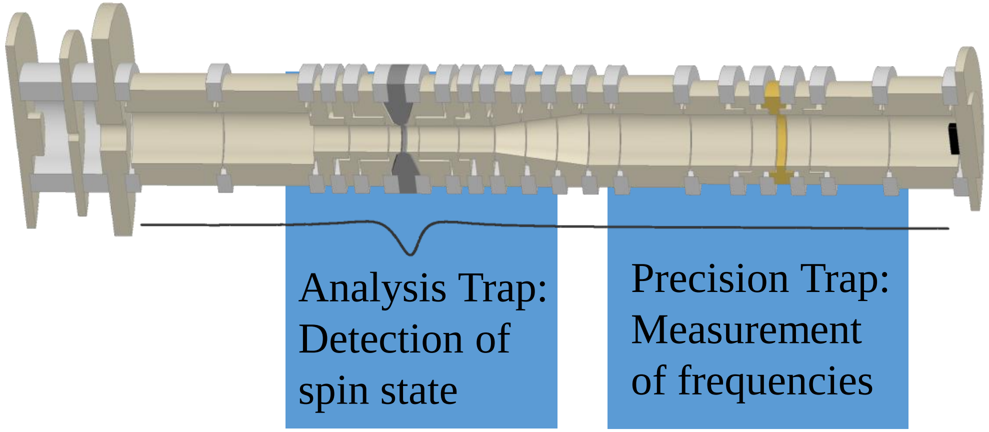
1. Stabilize energy fluctuations

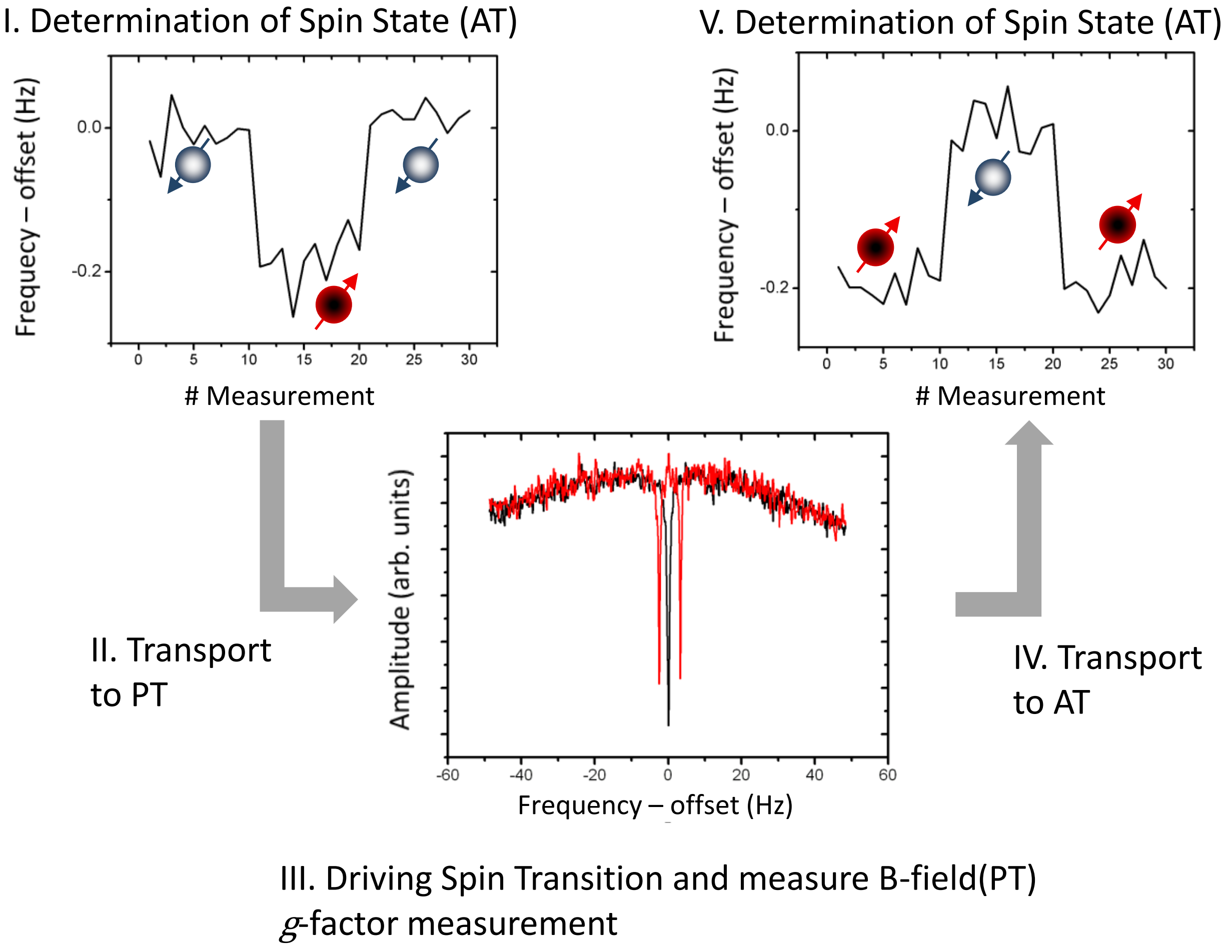
2. Reduce magnetic field inhomogeneity

Double Penning Trap Technique

- High Precision measurement demands homogeneous magnetic field
- Introduce two traps – double Penning trap setup

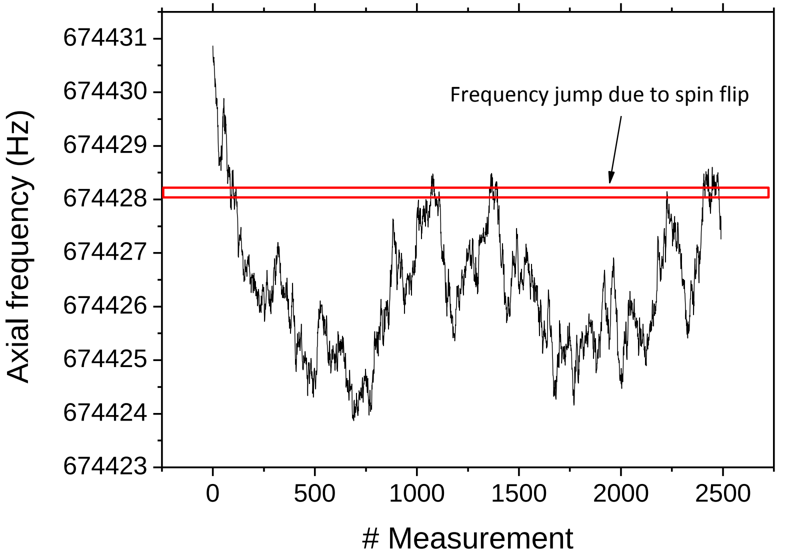
(H. Häffner, Phys. Rev. Lett.85, 5308 (2000))





Demands detection of every single spin transition!

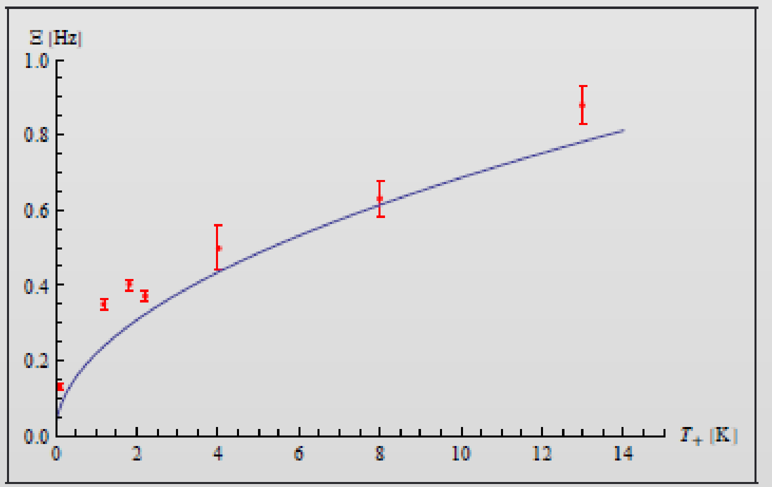
Origin of frequency fluctuations



Magnetic bottle coupling:

$$\Delta \nu_z = \frac{1}{4\pi^2 m \nu_z} \frac{B_2}{B_0} (dE_+ + dE_-)$$ -> 1 Hz/μeV

$$R_{n\to n\pm 1} = \frac{q^2}{2m_P \hbar\omega}\left(n + \frac{1}{2} \pm \frac{1}{2}\right) \underbrace{\int_{\mathbb{R}} dt' \, e^{\pm i\omega t} \left\langle E^{(1)}(t) E^{(1)}(t+t') \right\rangle}_{S(\pm\omega)}$$



Frequency fluctuation as function of T_+

Tiny heating of the axial mode results in significant fluctuation of the axial oscillation frequency. **-> Three cyclotron quanta (0.2 μeV) -> fidelity to 50%**

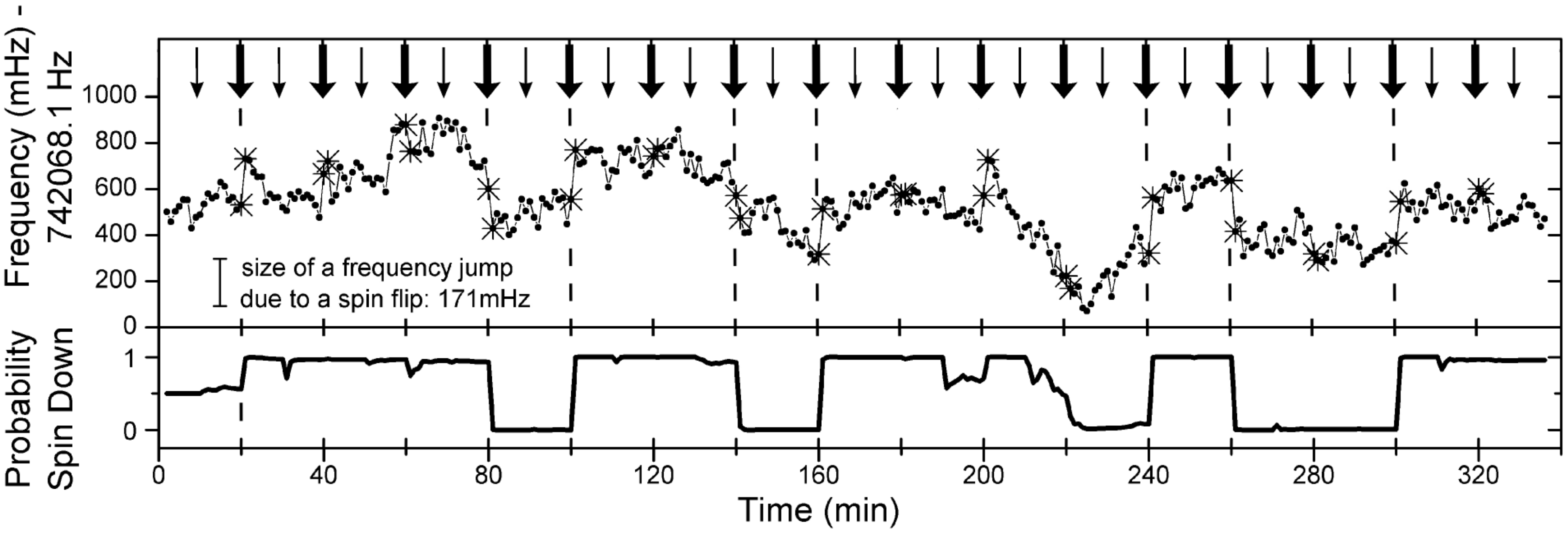
Important message: heating rates scale with the cyclotron quantum number!!!

Heating rates correspond to noise of some pV/Hz$^{1/2}$.

Detection of Spin State

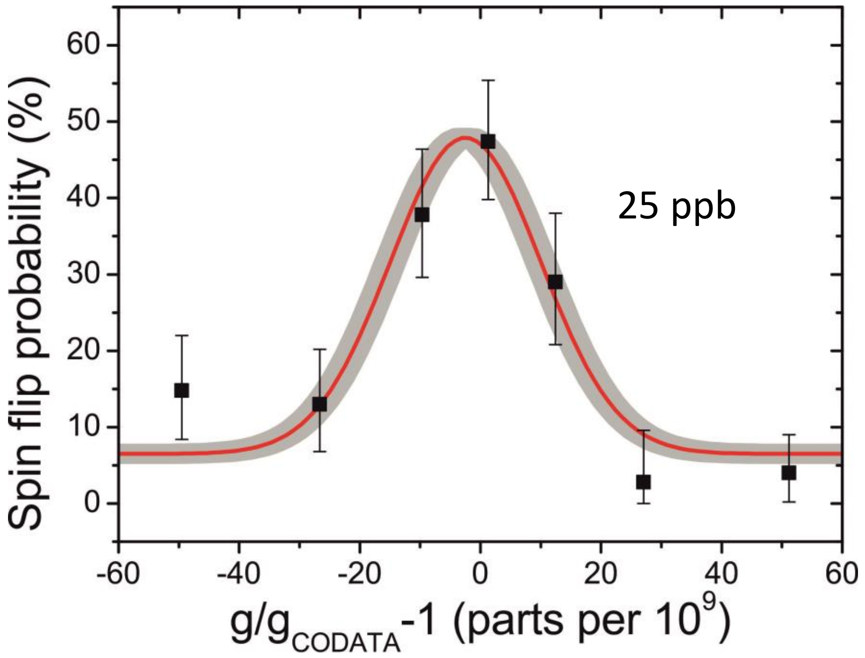
Series of axial frequency measurements in AT

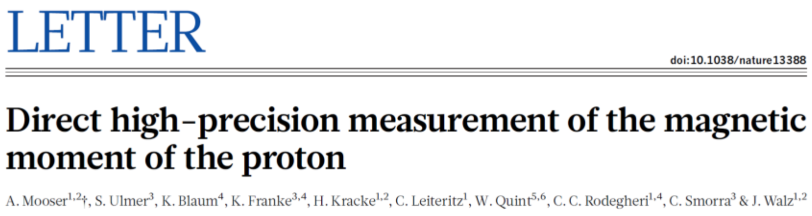
Apply resonant and off-resonant spin flip drives – background check



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

Direct High Precision Measurement for Proton




LETTER

doi:10.1038/nature13388

Direct high-precision measurement of the magnetic moment of the proton

A. Mooser[1,2]†, S. Ulmer[3], K. Blaum[4], K. Franke[3,4], H. Kracke[1,2], C. Leiteritz[1], W. Quint[5,6], C. C. Rodegheri[1,4], C. Smorra[3] & J. Walz[1,2]

$$g = 5.585\,694\,700(14)_{stat}(11)_{sys}$$

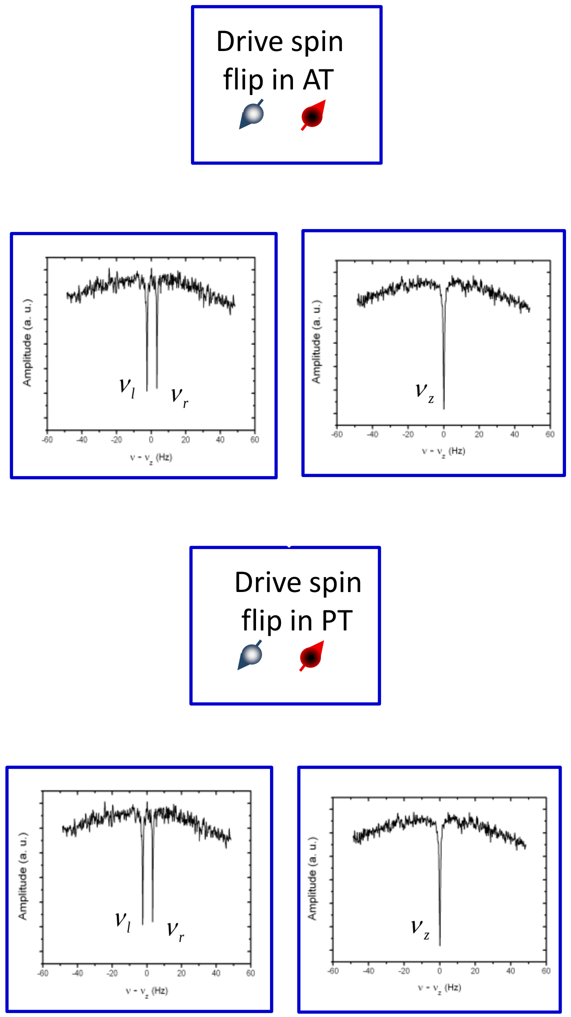
- First direct high precision measurement of the proton magnetic moment.
- Improves 42 year old MASER value by factor of 2.5 (P. F. Winkler *et al.*, Phys. Rev. A **5**, 83 (1972))
- Value in agreement with accepted CODATA value, but 2.5 times more precise

Systematic effects

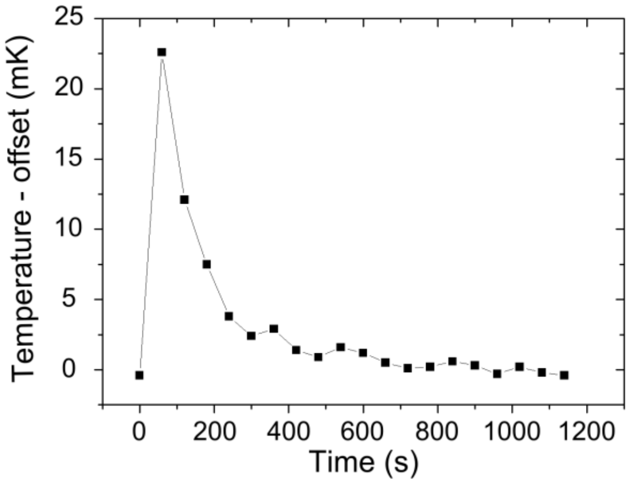
Parameter	Relative Shift of $g_p/2$	Uncertainty
Trapping Potential (C_4)	0	0.2 ppb
Relativistic Shift	0.030 ppb	<0.003 ppb
Image-Charge Shift	-0.088 ppb	<0.010 ppb
Nonlinear Magnetic Field Drift	0	2 ppb
Cyclotron Cooling	-0.51 ppb	0.08 ppb
Voltage Stability	-0.07 ppb	0.35 ppb
Total Systematic Shift	**-0.64 ppb**	**2 ppb**

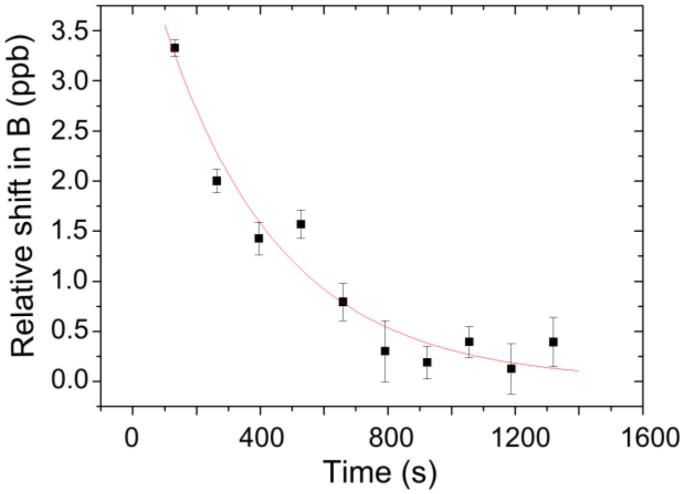
What are the dominant effects?

Dominant Systematic effect



Linear interpolation to compensate for magnetic field drifts. However nonlinear field drift observed



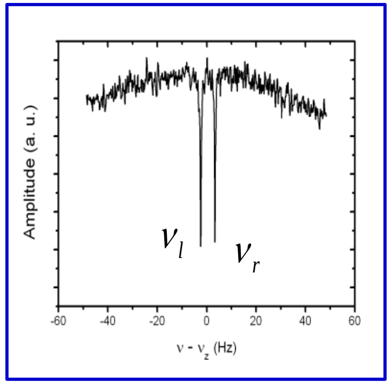


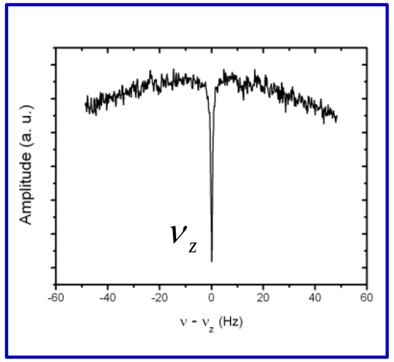
Heating caused by SF excitation in analysis trap

- Consistent with thermal expansion in the order 1µm
- Temperature-dependent susceptibility

Apply conservative systematic error of 2ppb on interpolated magnetic filed

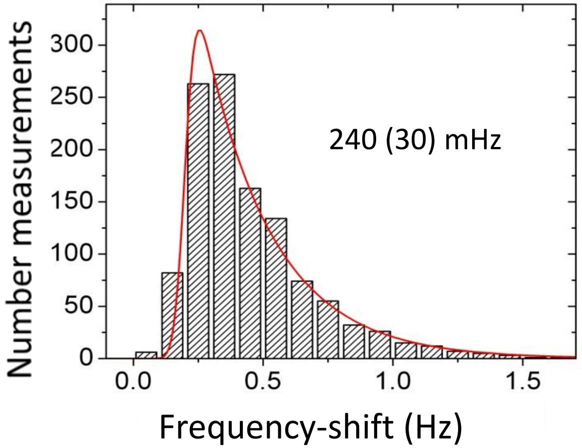
Dominant Statistical effect



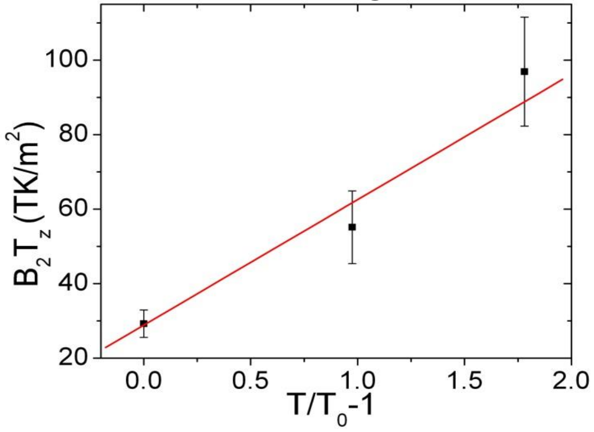


- Residual magnetic inhomogeneity in Precision trap due to Analysis Trap
- Measurement of axial frequency for different cyclotron energies in each run

$$\nu_z \propto \frac{E_+}{m} B_2$$



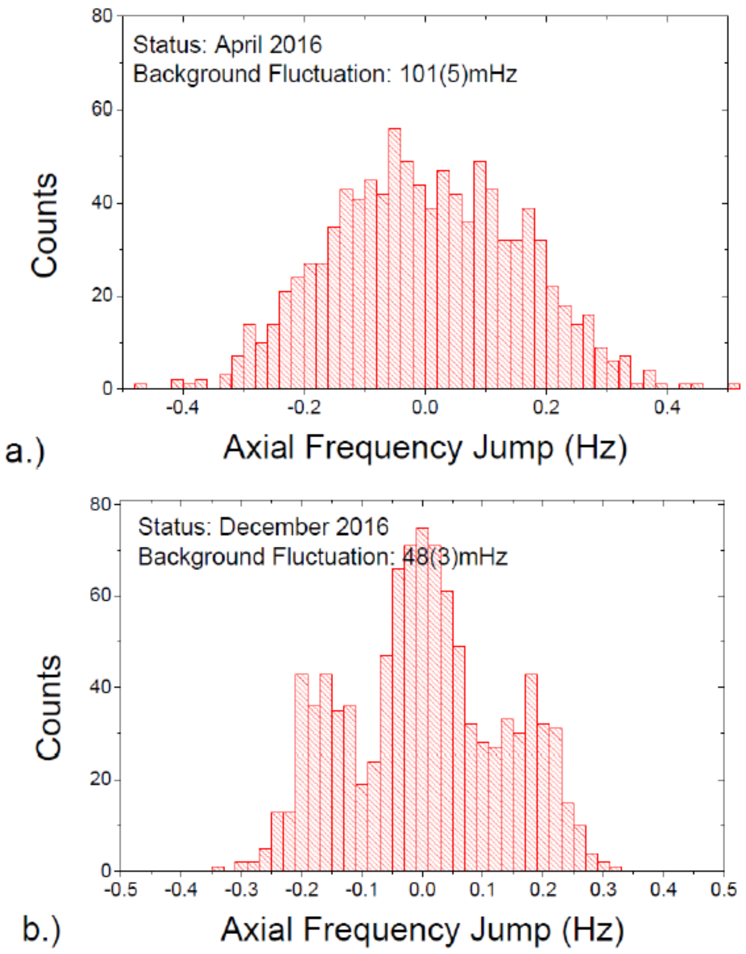
Crosscheck using feedback



- Scatter in axial frequency measurements
- Cases scatter in cyclotron frequency measurements – broadens resonance line

$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$$

Single antiproton spin transitions



Status after the 0.8 ppm
antiproton g-factor measurement

Axial frequency stability: 101 mHz
Spin flip frequency shift: 170 mHz

Suppression of voltage noise densities of order
10 – 100 pV / SQRT(Hz) is challenging!

This noise can be measured only by a
single antiproton in a strong magnetic bottle

Axial frequency stability after optimization: 48 mHz

Single antiproton spin transitions

Physics Letters B 769 (2017) 1–6

Contents lists available at ScienceDirect

Physics Letters B

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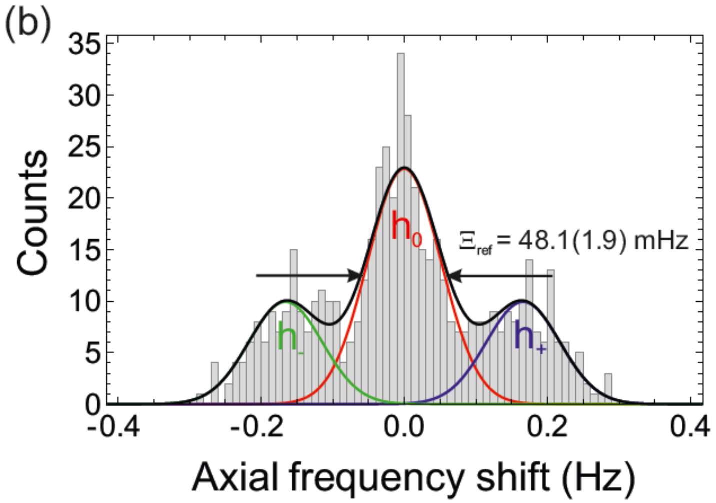
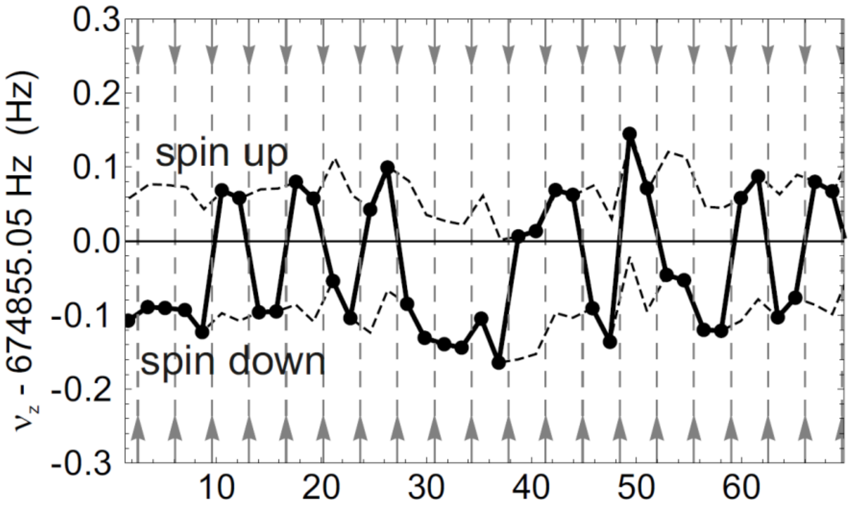
Observation of individual spin quantum transitions of a single antiproton

- Single spin transitions can be identified with a high fidelity (Average spin-state fidelity > 92 %)
- Enables an antiproton g-factor measurement with the double-trap method





Results

- Proton-antiproton charge-to-mass ratios compared with highest precision

$$\frac{(q/m)_{\overline{\mathrm{p}}}}{(q/m)_{\mathrm{p}}}+1 = 1(69) \times 10^{-12}$$

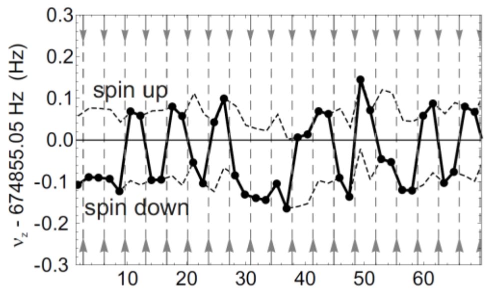
- Measurement of antiproton g-factor

$$\frac{g_{\bar{p}}}{2} = 2.7928465(23)$$

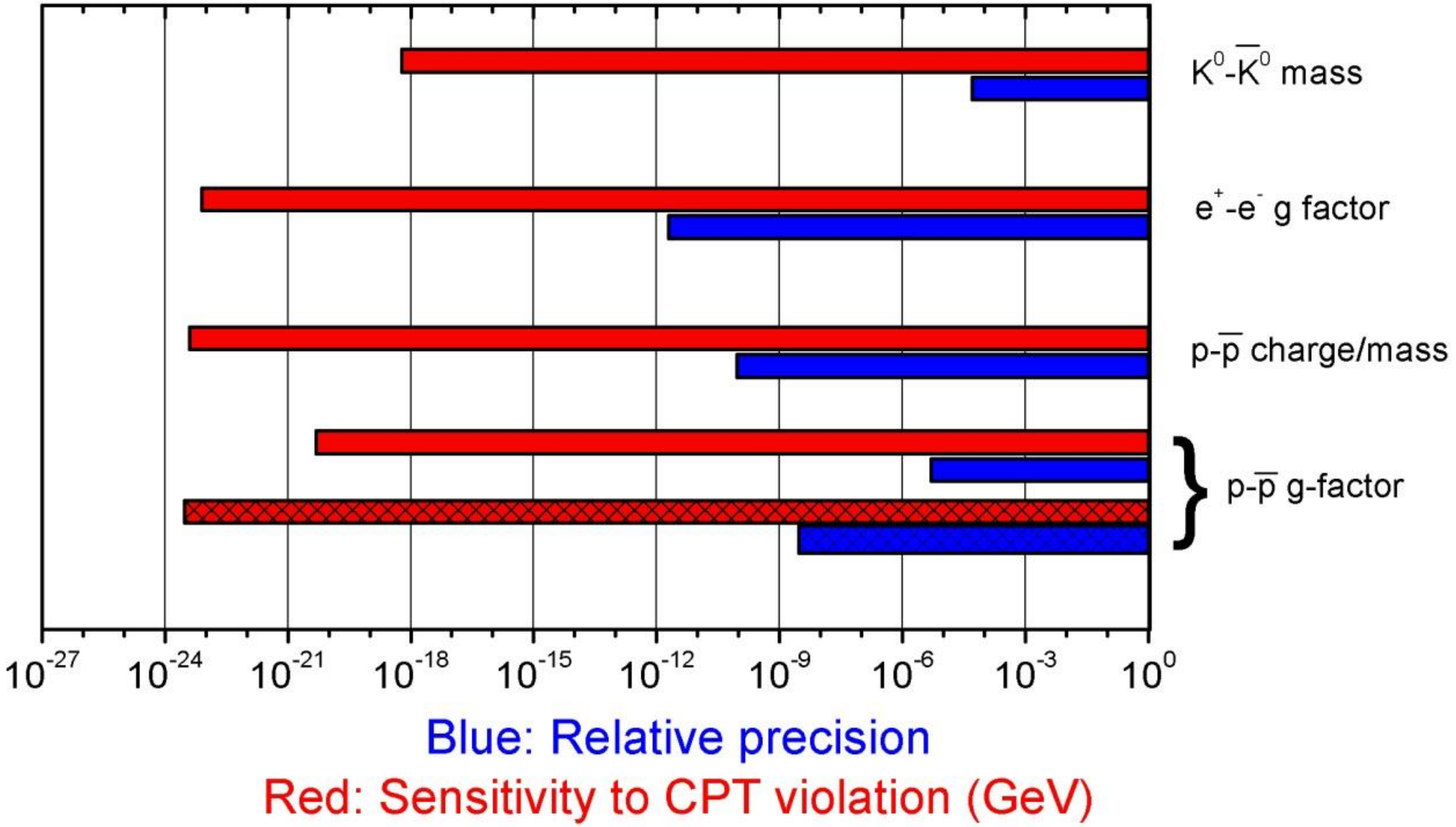
- High precision measurement of the proton g-factor using the double-trap technique:

$$\frac{g_p}{2} = 2.792847350(9)$$

- Outlook: Antiproton g-factor measurement with the double trap method



CPT - Sensitivety



Sympathetic Laser cooling

Future of Nuclear Magnetic Momenets and Helion (^3He)

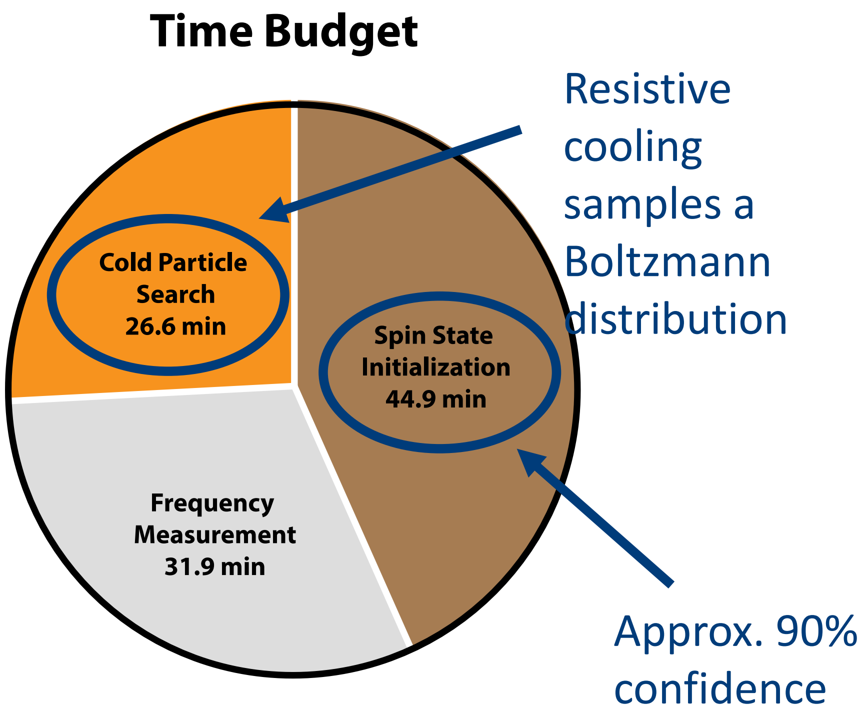
Why Laser cooling?

Now thermal coupling to thermal bath

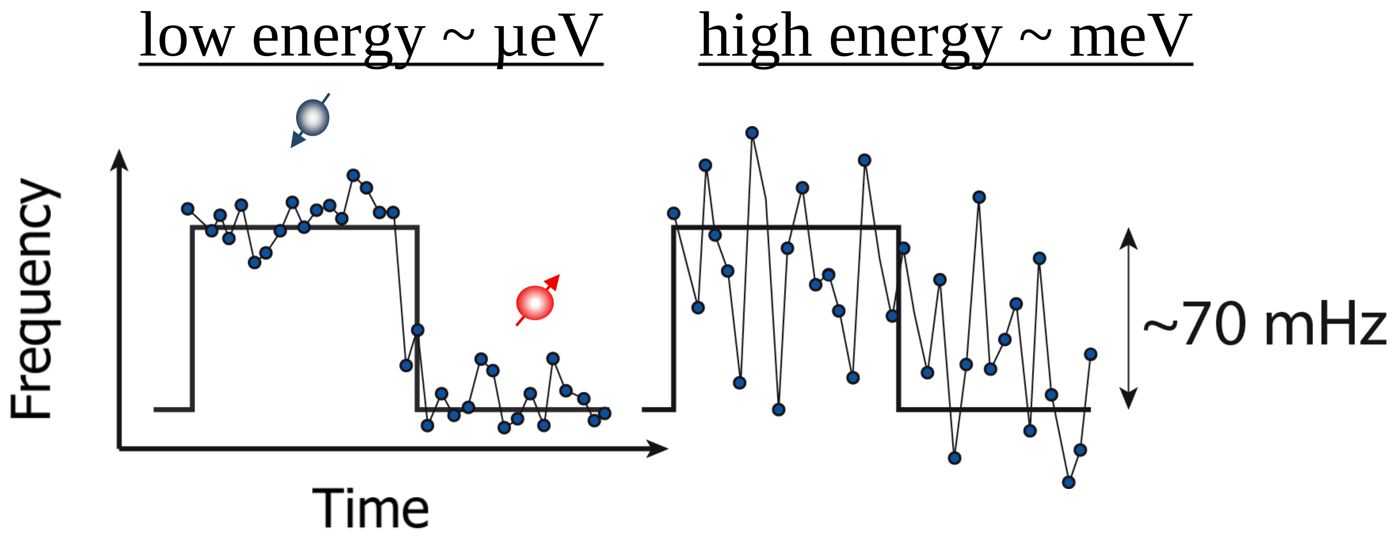
- Limited temperature 4K
- Slow – several minutes
- Statistical Process – several trials needed

Future Laser cooling

- Low temperatures oder mK
- Fast – Linewidth of 19 MHz hence ms
- Quasi deterministic cooling compared to thermal temperatures

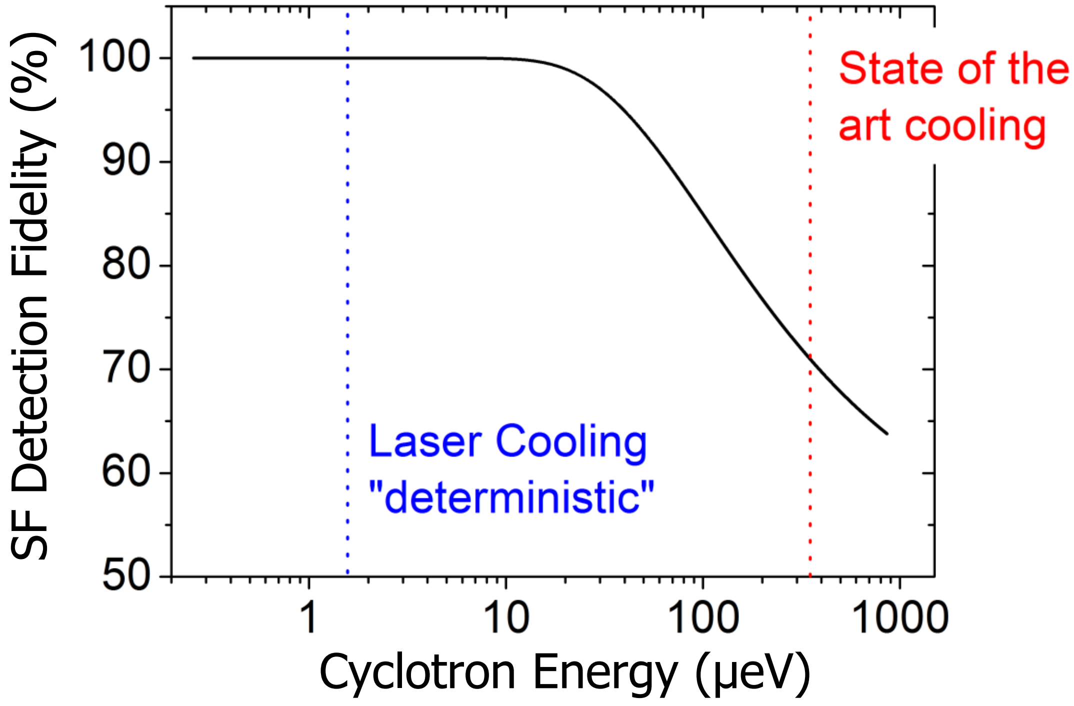


Key technique for heavier ions - Helion – ^{3}He



Signal for ^{3}He: $$\frac{S_{Helium}}{S_{Electron}} \approx \frac{1}{900}$$

Noise for ^{3}He: $$\frac{N_{Helium}}{N_{Proton}} = 4$$

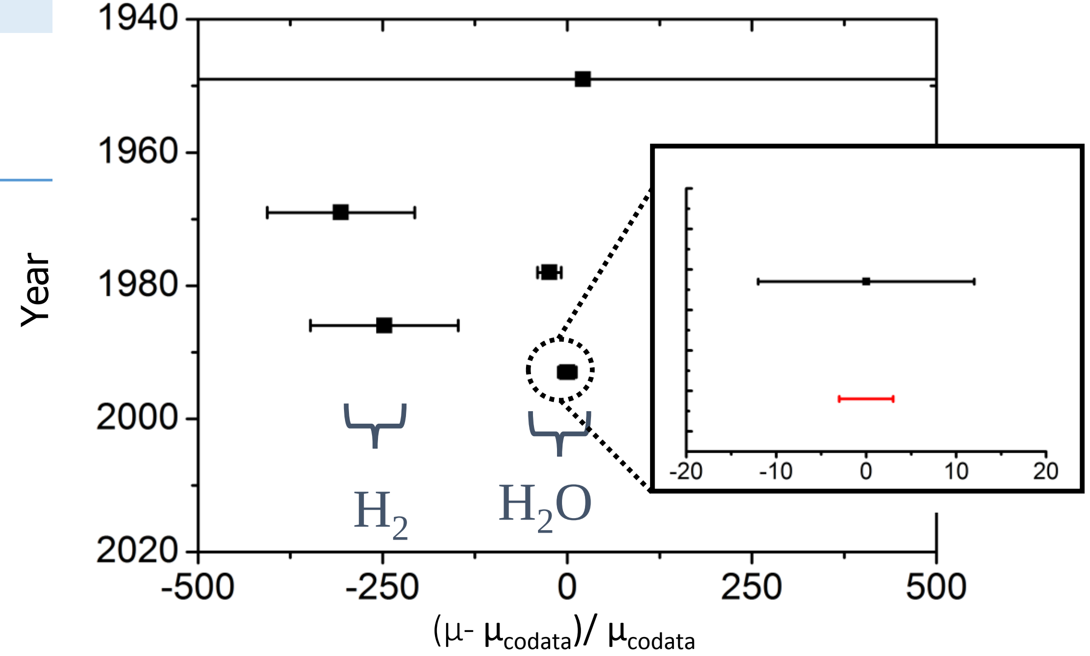


What's interesting about Helion?

- Hyperpolarized ^3He as new standard in magnetometry

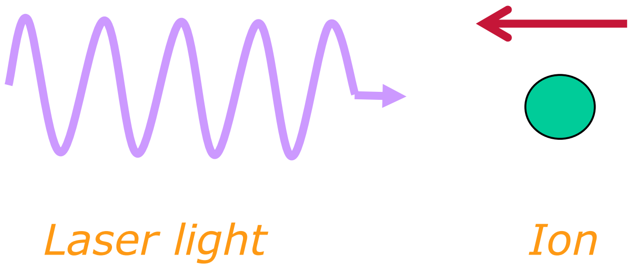
	Water NMR		^3He
Dependence on temperature	1		1/100
Dependence on probe shape	1	>	1/1000
Diamagnetic shielding	1 measured	>	1/10 calculated

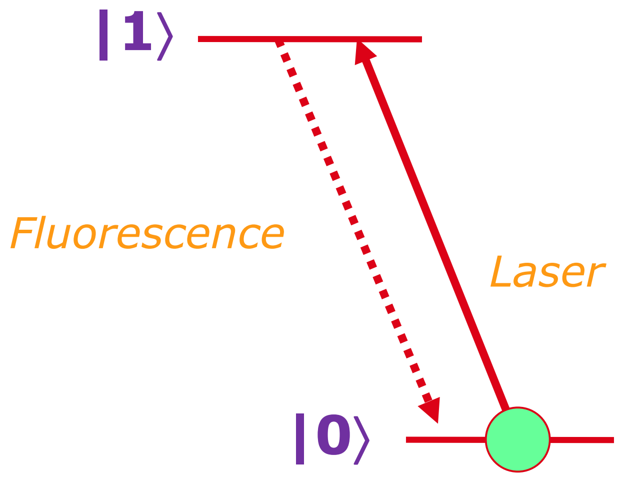
- $\Delta B/B = 10^{-12}$ in seconds using hyperpolarized ^3He



Basic Idea

- We use radiation pressure for laser cooling of ions
  - Same principle as for Doppler cooling of atoms
  - Laser excites the ion to an excited state, slows it down slightly
  - An ion with v ~ 500 m s^{-1} can be stopped in 1 ms (10^5 cycles)
- Force must be turned off when ion moving away from laser
  - Otherwise the process will reverse and it will speed up again
  - So set laser frequency just below ion resonance
- Minimum temperature (Doppler limit) is ~1mK





First Lasercooling in a trap

- First laser cooling demonstration (Wineland et al 1978) used the “Bolometric technique” – detect electrical noise across electrodes due to ion motion

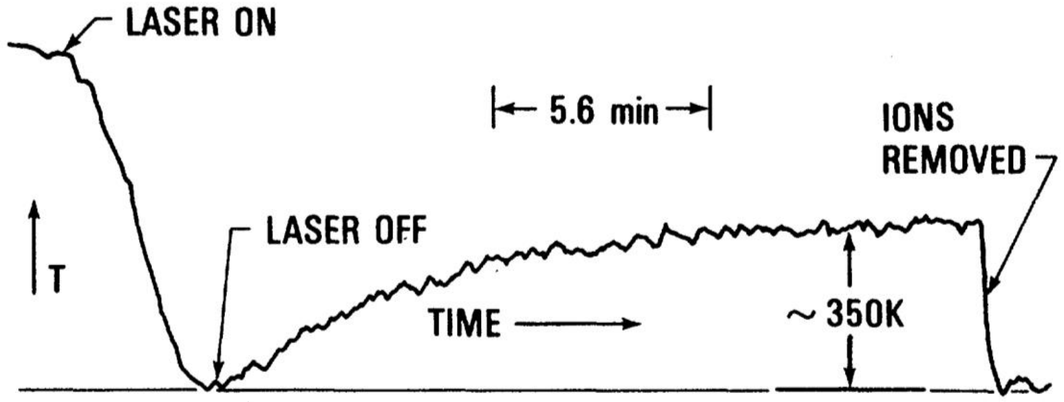
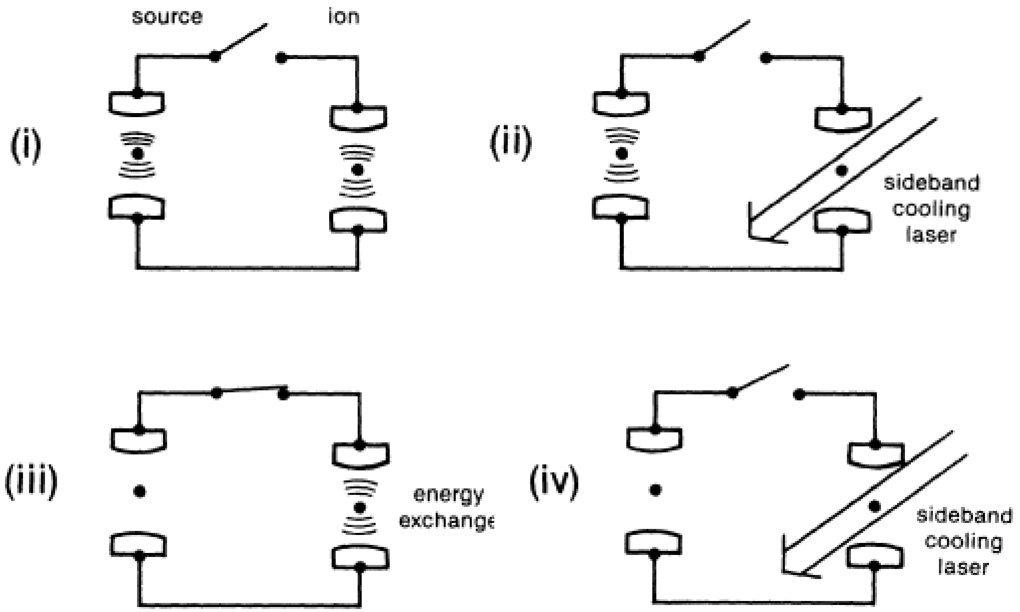


FIG. 2. Ion temperature vs time when laser cooling is applied for fixed $\nu_L - \nu_0$. The ions were initially heated above equilibrium temperature with the laser. Laser cooling was then applied on the $-\frac{1}{2} \leftrightarrow -\frac{3}{2}$ transition for a fixed time until a temperature approaching 0 K (< 40 K) was achieved. After the laser is turned off, the ions rethermalize to the ambient temperature.

Sympathetic laser cooling

- Sympathetic cooling – no addressable internal states for proton/antiproton
- Proposal by D.J. Wineland in the 1990ies



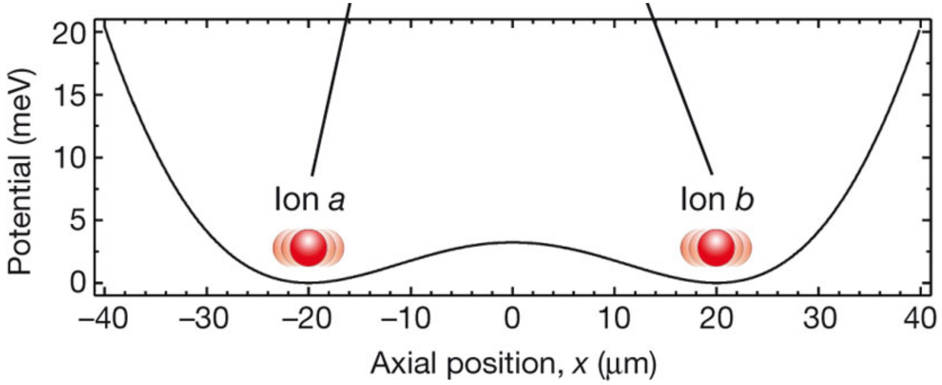
Two Options...

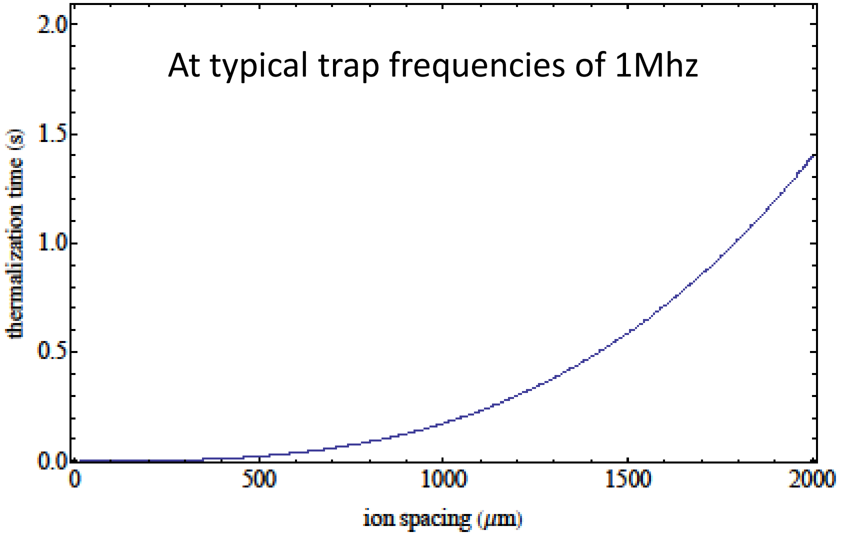
Heinzen and Wineland Phys. Rev. A 42, 2977 (1990)

Option I – Direct coulomb coupling

- Direct Coulomb coupling with ions at close proximity

$$\Omega_{ex} \equiv \frac{q_a q_b}{4\pi\varepsilon_0 s_0^3 \sqrt{m_a m_b}\sqrt{\omega_{0a}\omega_{0b}}}$$





- Coupling times in the order of seconds
- Increases for additional Be ions

- Demands development of „miniature“ Penning trap which allows for small ion separations at equal oscillation frequencies
- Beeing implemented at BASE HANNOVER

Option II – Common Endcap coupling

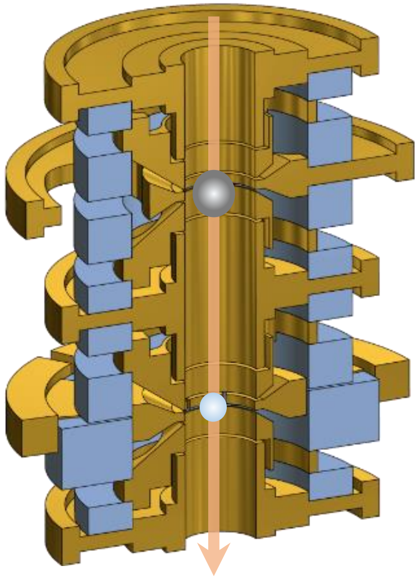
- Interaction via image currents induced in trap electrodes (proposal by D. J. Wineland)

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

- Allows usage of established trap designs
- Better control over static trapping fields

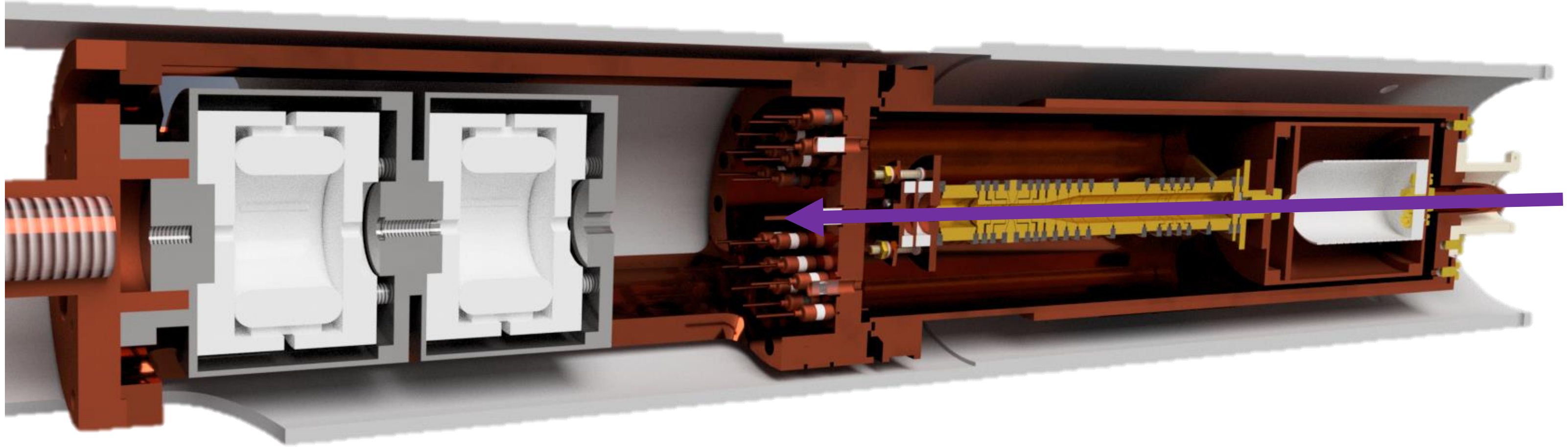
- However coupling times in the order of 30sec

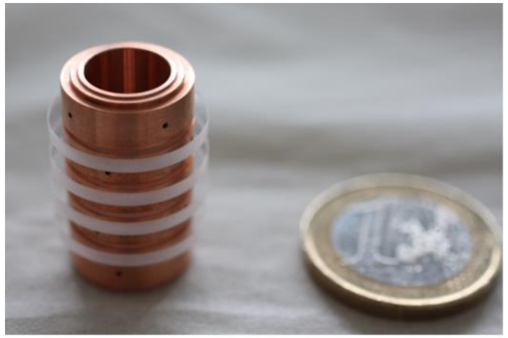
- Beeing implemented at BASE Mainz

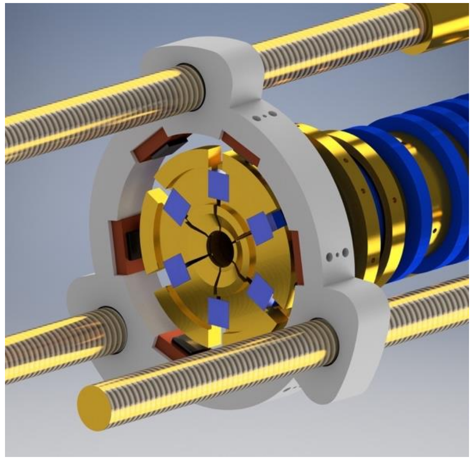


Based on existing design - optimized for low trap capacitance

Setup– Common Endcap coupling





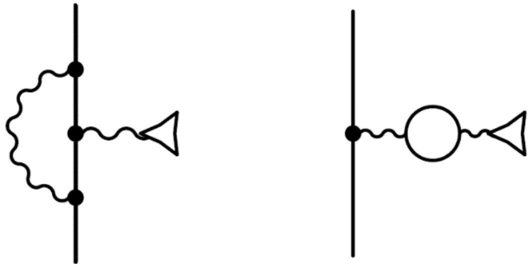


G-Factor in highly charged ions

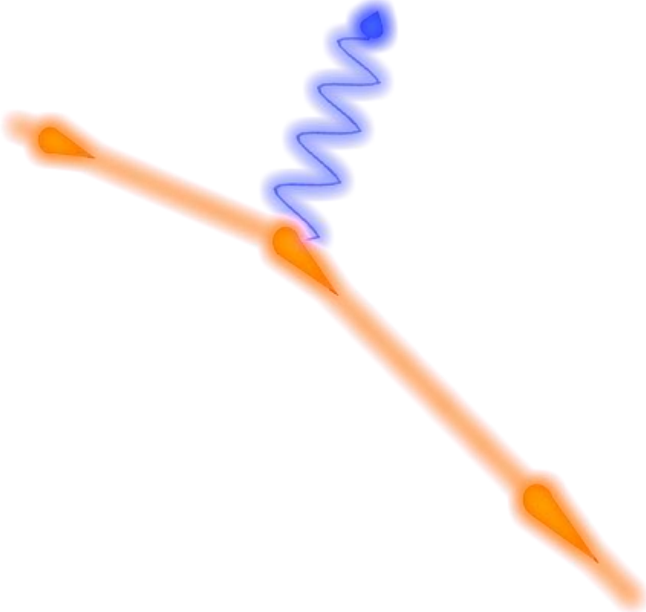
Quantum Electrodynamics

QED describes the quantum interaction of
light (photons) and ***matter*** (charged particles)

through a series of simple fundamental interaction processes depicted by
Feynman diagrams



Richard P. Feynman



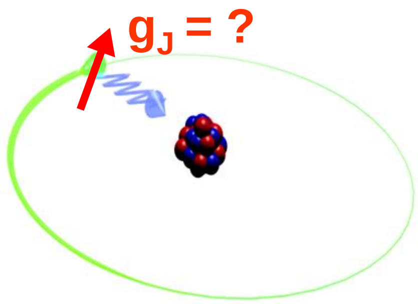
Calculated values are in impressive agreement with experimental results

QED is our <u>best tested</u> theory in weak fields

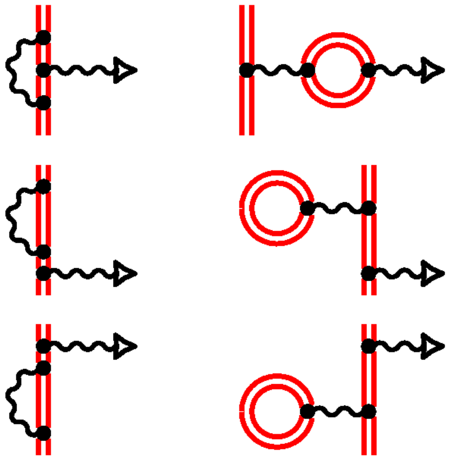
However: Lack of tests in extreme situations

G-Factor of the bound electron

Primary goal: test of QED in strong fields



Changes to the free-electron case:



1st order terms

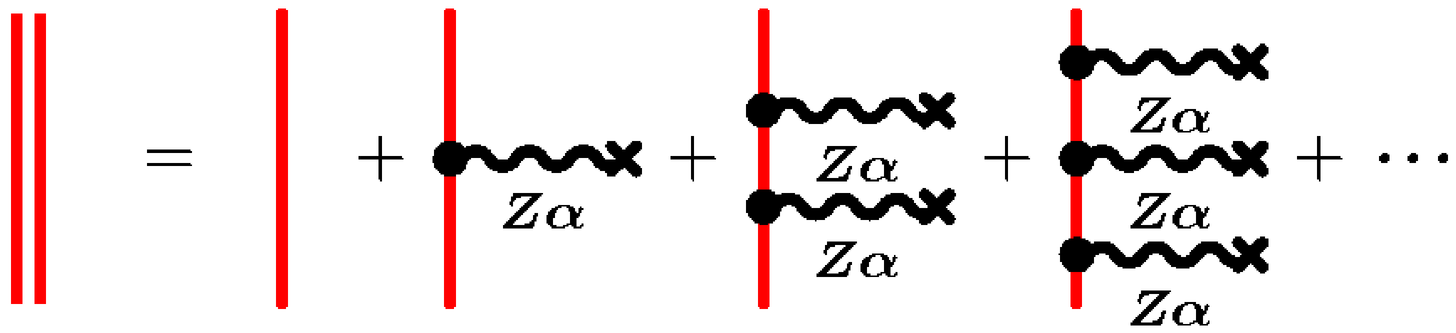
1. Spin is no longer „good quantum number“ but total angular momentum g_J

$$g_{J\,Dirac} = 2\left(\frac{2\sqrt{1-(Z\alpha)^2}+1}{3}\right) = 2 - \frac{2}{3}(Z\alpha)^2 + \cdots$$

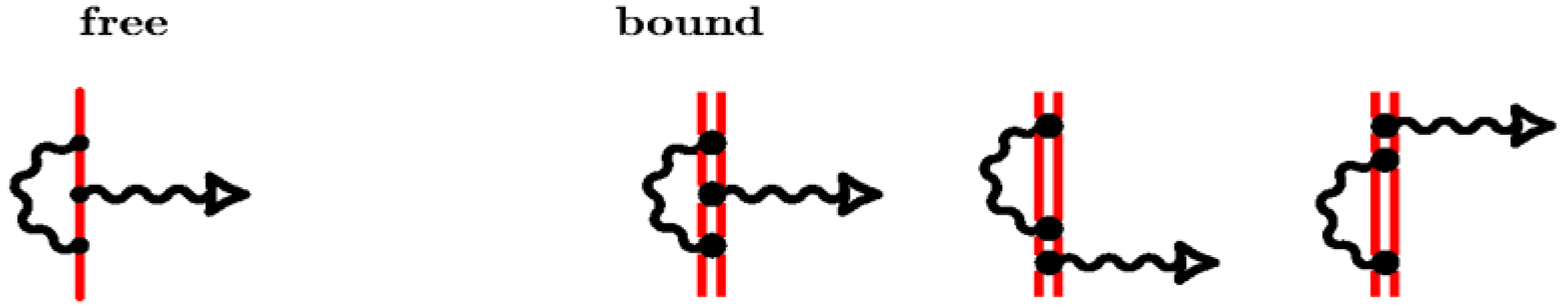
2. QED has to take into account the effect of binding

3. Nuclear effects have to be considered

From free to bound state QED



Additional QED corrections of order (Zα/π)

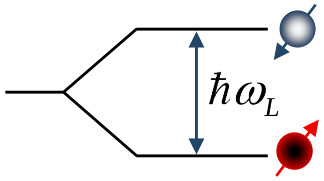


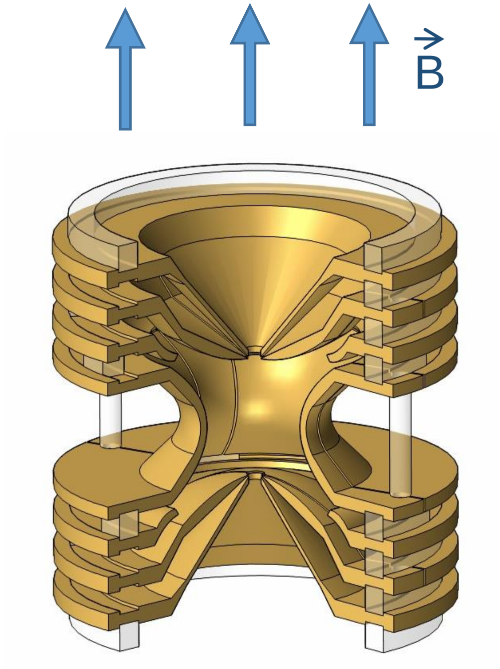
Self energy corrections

Measurement principle

Determination of Larmor frequency in a given magnetic field

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

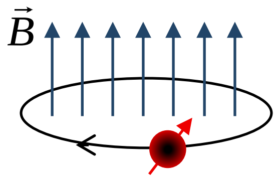




$$g = 2\frac{\omega_L}{\omega_c}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e} = 2\Gamma\frac{q_{ion}}{m_{ion}}\frac{m_e}{e}$$

Monitoring magnetic field via simultaneous measurement of the free cyclotron frequency

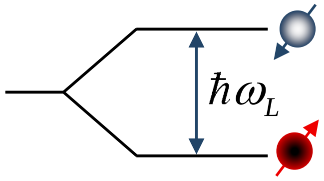
$$\omega_c = \frac{q_{ion}}{m_{ion}}B$$

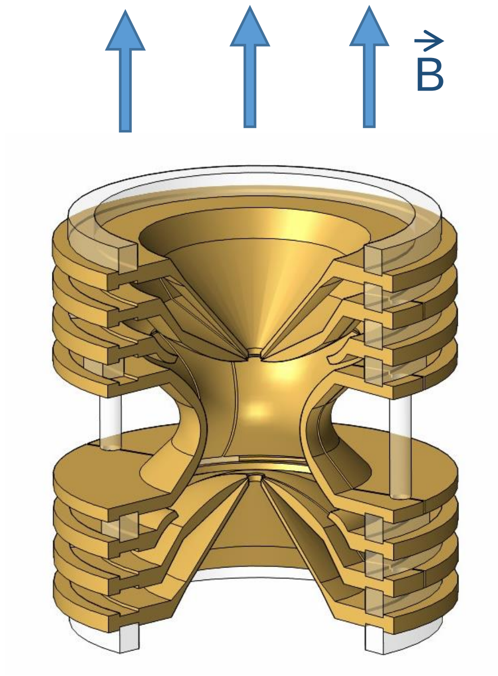


Measurement principle

Determination of Larmor frequency in a given magnetic field

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





Monitoring magnetic field via simultaneous measurement of the free cyclotron frequency

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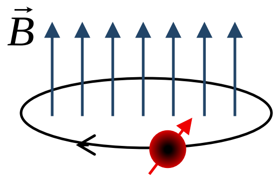
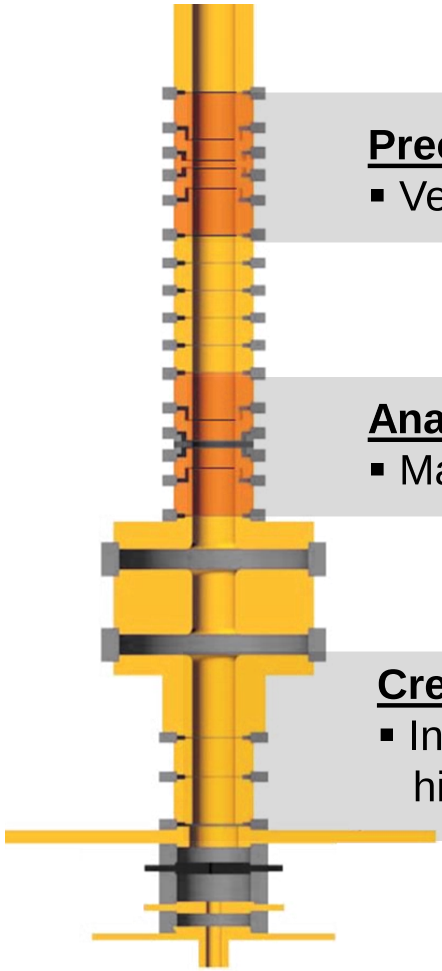


$$g = 2\frac{\omega_L}{\omega_c}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e} = 2\Gamma\frac{q_{ion}}{m_{ion}}\frac{m_e}{e}$$

Measured

Measured independently

Triple trap setup



Precision trap (PT)
- Very homogeneous magnetic field

Analysis trap (AT)
- Magnetic bottle for spin detection

Creation trap (CT)
- In-trap ion creation of highly-charged ions

Double trap method

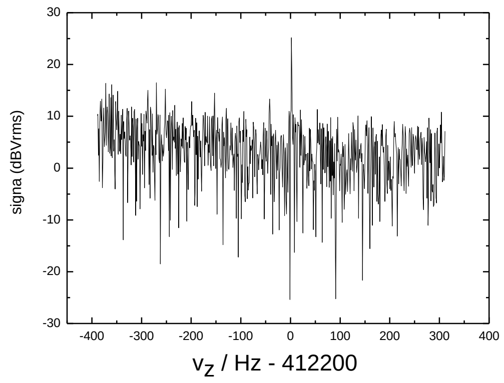
Phasesensitive Frequency measurement

Until now incoherent detection techniques:

– Precision scaling $\sqrt{T}$: long measurement time (1-3 min.)

→ increases impact of magnetic field fluctuations

– statistical precision limited by the linewidth of the dip



Basics of phase detection:

$$\nu = \frac{1}{2\pi} \frac{\varphi_{start} - \varphi_{stop}}{T_{evol}}$$

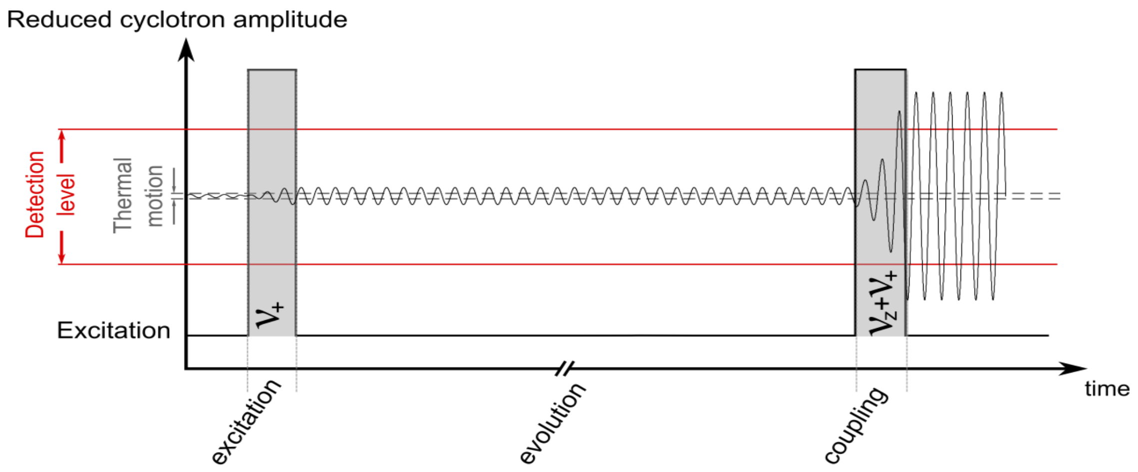
$$\delta\nu = \frac{1}{T_{evol}} \sqrt{(\delta\varphi_{start})^2 - (\delta\varphi_{stop})^2}$$

Advantages:

- faster measurement method
- no lineshape model needed
  → reduces systematic uncertainty

Puls and Phase methode

Phase sensitive measurement allowing measuement of the modified cyclotron frequency, ν_+:



with the following advantages:

✓ rapid measurement time (~ 5s instead of ~ 3min)
→ reduction of impact of B-field fluctuations

✓ small radial kinetic energies during phase evolution
→ smaller magnetic and relativistic shifts

Measurement on hydrogen-like carbon ($^{12}C^{5+}$)

LETTER

doi:10.1038/nature13026

High-precision measurement of the atomic mass of the electron

S. Sturm[1], F. Köhler[1,2], J. Zatorski[1], A. Wagner[1], Z. Harman[1,3], G. Werth[4], W. Quint[2], C. H. Keitel[1] & K. Blaum[1]

$$g^*_{th}(^{12}C^{5+}) = 2.001\,041\,590\,179\,8(47)$$

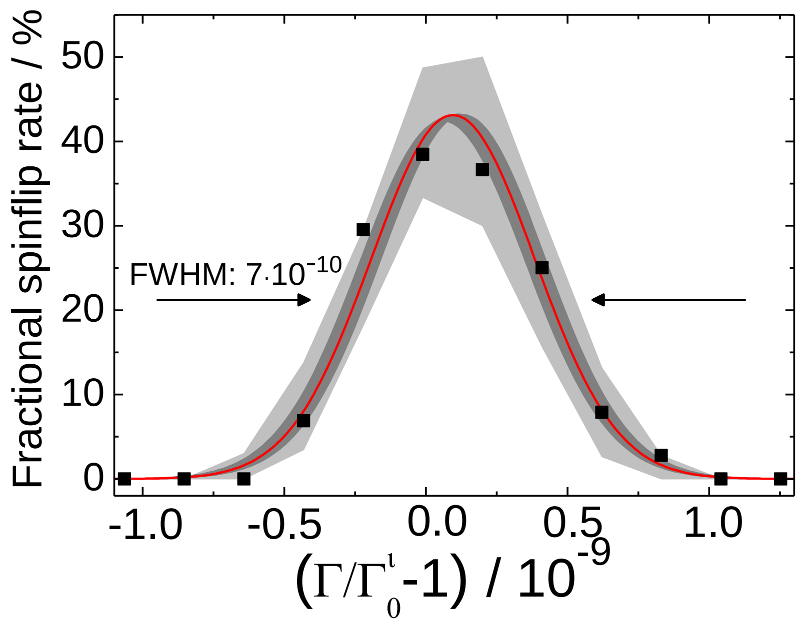
Uncertainty: higher order QED

$$g_{\mathrm{meas}}(^{12}C^{5+}) = 2.001\,041\,592\,44\,(232)(5)(3)$$

Mass of the electron: 540ppt

Statistical uncertainty: 2.3·ppt

Dominant systematics: image charge shift - 14 ppt



Determination of the mass of the electron

Turn arguments around:

Believe that QED is correct and compare experiment with theory

$$g_{exp} = 2\Gamma_{exp} \frac{q_{ion}}{m_{Carbon}} \frac{m_e}{e}$$

$$g^*_{th}(^{12}C^{5+}) = 2.001\,041\,590\,179\,8(47)$$

$$g_{meas}(^{12}C^{5+}) = 2.001\,041\,592\,44\,(232)(5)(3)$$

Known by definition – atomic mass reverence

Most precise determination:

m_e=0,000 548 579 909 067 (14)(9)(2) u (30ppt)

(stat)(syst)(theo)

Provit from an improved electron mass

Important ingredient in fine-structure constant measurement:

$$\alpha \equiv \frac{e^2}{2\varepsilon_0 hc} \qquad \alpha^2_{recoil} = \frac{2R_\infty h}{cm_e} = \frac{2R_\infty}{c}\frac{M_{Rb}}{m_e}\frac{h}{M_{Rb}}$$

→ Improve most stringent QED test:

- comparison : $\alpha_{recoil} \Leftrightarrow \alpha_{g-factor\ \ free\ electron\ and\ theory}$

$$a_e = A_1\frac{\alpha}{\pi} + A_2\left(\frac{\alpha}{\pi}\right)^2 + A_3\left(\frac{\alpha}{\pi}\right)^3 + A_4\left(\frac{\alpha}{\pi}\right)^4 + \ldots + a\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}, weak, hadron\right)$$

→ physics beyond Standard Model

Provit from an improved electron mass

Important ingredient in fine-structure constant measurement:

$$\alpha \equiv \frac{e^2}{2\varepsilon_0 hc} \qquad \alpha^2_{recoil} = \frac{2R_\infty h}{cm_e} = \frac{2R_\infty}{c}\frac{M_{Rb}}{m_e}\frac{h}{M_{Rb}}$$

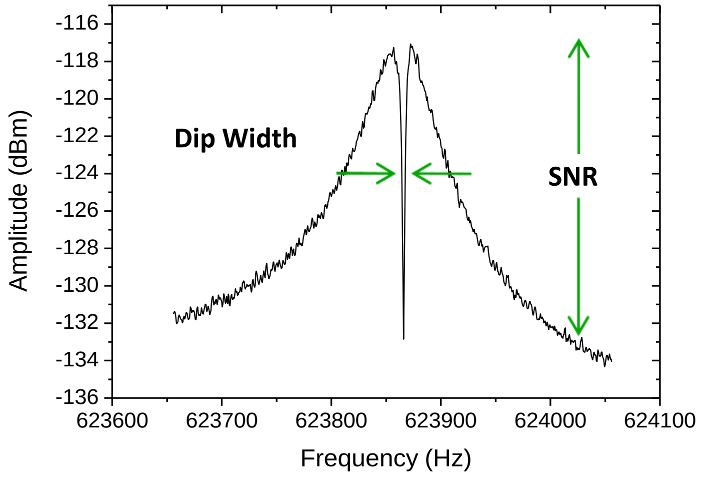
Hint for physics beyond SM: discrepancy at muon *g*-2 (0.54 ppm)
enhanced sensitivity due to mass: $(m_\mu/m_e)^2$=40000

Independent α: precision of 37ppt for could check this effect with the electron

- α from the free electron *g*-factor and theory has to improve by a factor of 8
- α_{recoil} has to improve by a factor of 20
- *precision of m_e (30ppt) now sufficient*

Ersatz Folien

Improvement of axial frequency stability

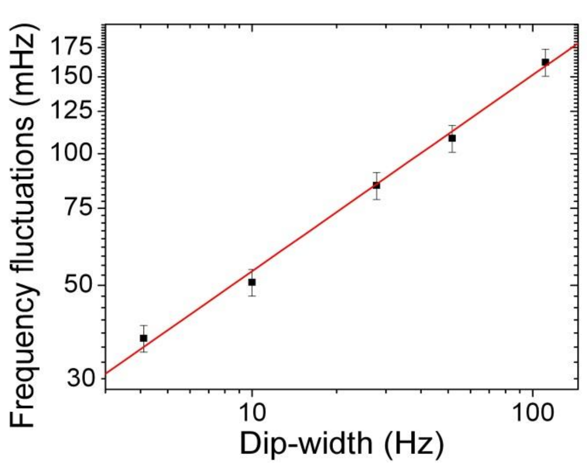


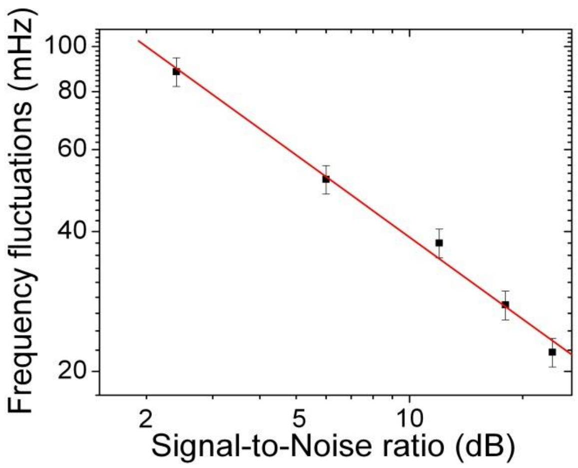
Higher signal-to-noise ratio $SNR \propto R_p \propto Q$

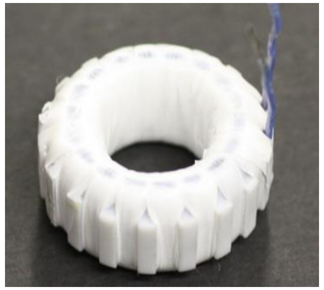
results in improved frequency measurement in but $$\delta\nu_z = \frac{1}{2\pi}\frac{q^2}{m}\frac{R_p}{D}$$

Can be overcome by increased effective
Electrode distance *D*

$Q = 12000$
$R_P = 120\ M\Omega$
$u_n = 0.9\, nV/\sqrt{Hz}$







Provit from an improved electron mass

- Important ingredient in fine-structure constant measurement:

$$\alpha \equiv \frac{e^2}{2\varepsilon_0 hc}$$

5 ppt, CODATA (T. Hänsch) 2010

115 ppt, E. Myers 2010

$$\alpha^2_{recoil} = \frac{2R_\infty h}{cm_e} = \frac{2R_\infty}{c}\frac{M_{Rb}}{m_e}\frac{h}{M_{Rb}}$$

1241 ppt, F. Biraben 2011

$$v_{recoil} = \frac{\hbar k}{M_{Rb}}$$

30 ppt, This value

→ Improve most stringent QED test:

- comparison : $\alpha_{recoil} \Longleftrightarrow \alpha_{g-factor\ \ free\ electron\ and\ theory}$

$$a_e = A_1\frac{\alpha}{\pi} + A_2\left(\frac{\alpha}{\pi}\right)^2 + A_3\left(\frac{\alpha}{\pi}\right)^3 + A_4\left(\frac{\alpha}{\pi}\right)^4 + \ldots + a\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}, weak, hadron\right)$$

→ physics beyond Standard Model

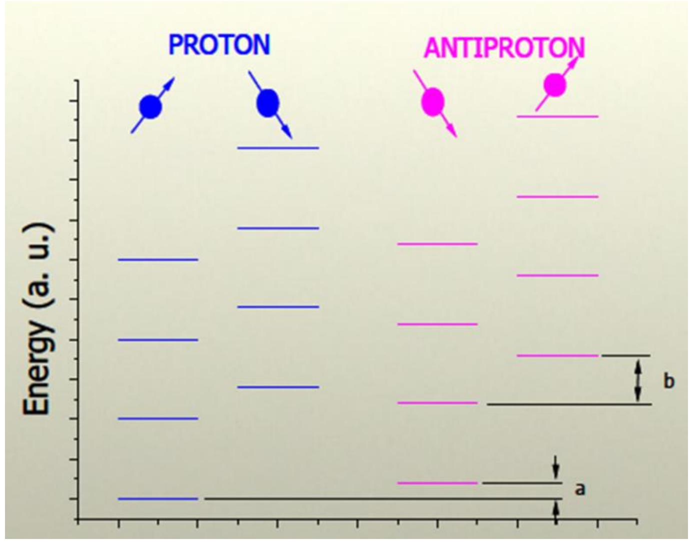
→ inner structure of electron

→ light dark matter hypothesis

Proton and Antiproton

- Introduce CPT And Lorentz violating terms to Standard Model while preserving Poincare-Symmetry

$$\left(i\gamma^{\mu}D_{\mu} - m - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma^{5}\gamma^{\mu}\right)\psi = 0$$



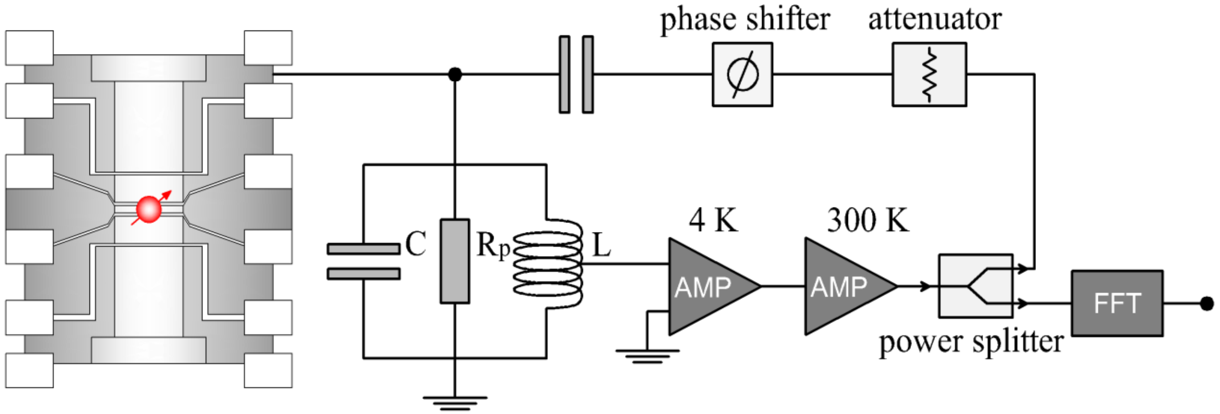
- a_{μ} – shifts levels, no measurable effect in Penning trap
- b_{μ} – modification of anomaly frequency $\omega_L - \omega_c$

- Diurnal variations in anomaly frequency predicted – anisotropy due to b_{μ}

- CPT violating extensions as small pertubation – contributions at absolute energy scale

➡ High sensitivity – measurement at small intrinsic energy scales – here nuclear magneton

Feedback Cooling

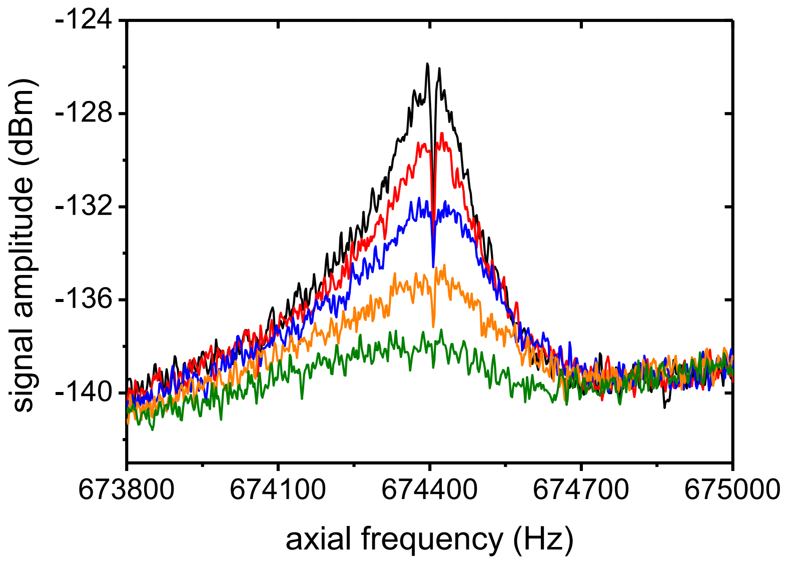


$$R_{FB} = R_p \left(1 \pm G_{FB}\right)$$
$$T_{FB} = T_0 \left(1 \pm G_{FB}\right)$$

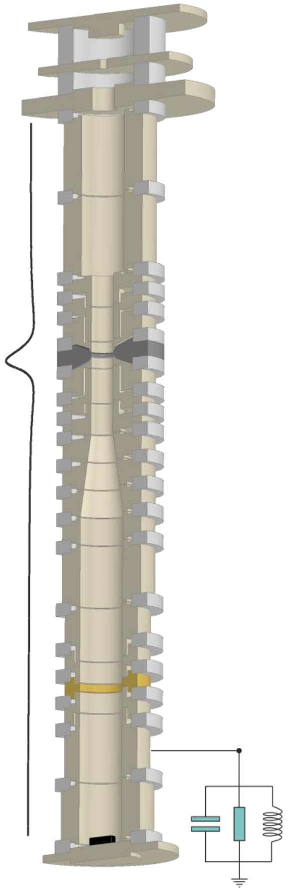
- Particle signal is fed back to the trap
- Particle temperature becomes adjustable:

Negative feedback: lower temperature, smaller oscillation amplitude, narrower linewidths.

Positive feedback: higher temperature, higher signal-to-noise ratio, shorter measuring time.



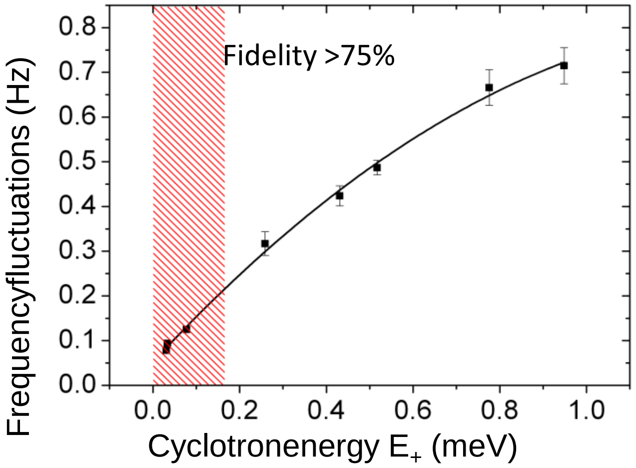
Double Trap Method

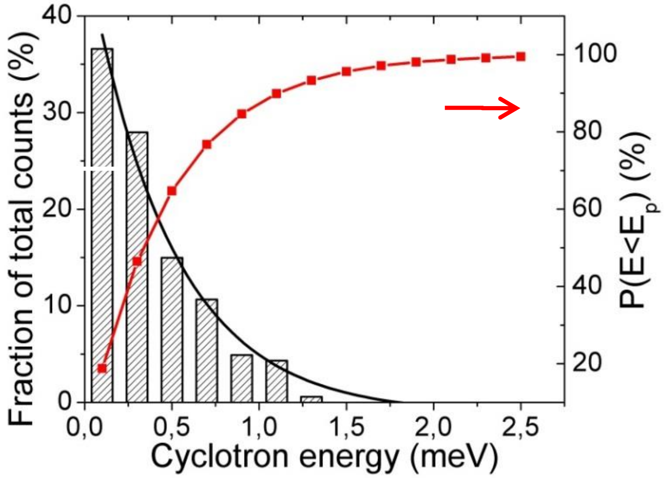


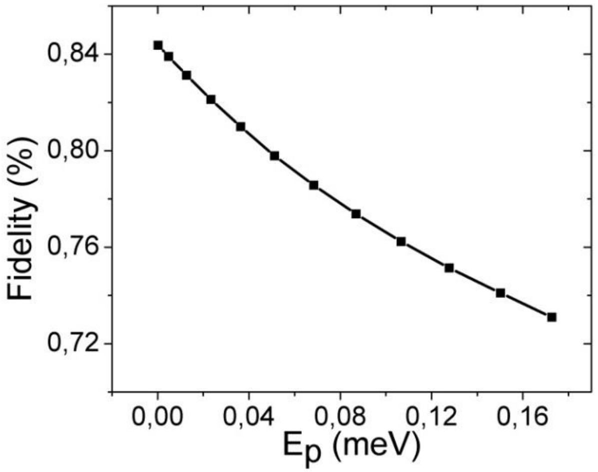
Cyclotron frequency measurement heats cyclotron mode to 30 meV

Low energies required in analysis trap for high fidelity spin state detection

In analysis trap







Coupling to thermal bath in precision trap

Preparation of subthermal E_+ 3 hours for one spin flip trail in precision trap with fidelity of 75%

Next step sympathetic Laser cooling

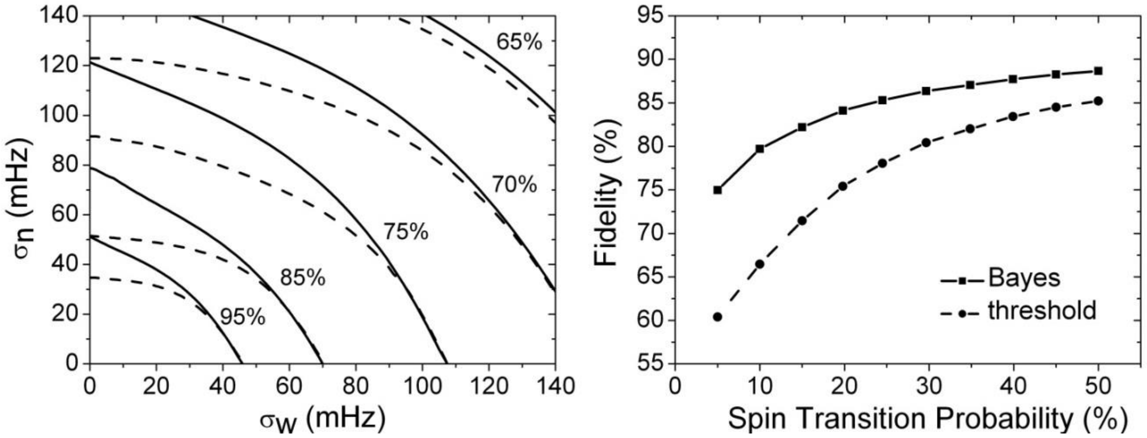
Improvement of spin state detection quality

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

Bayes rule – conditional probability of having a spin state $P(S \mid f_2, f_1) \propto P(f_2 \mid S, f_1) P(S, f_1)$

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%