Atomic Physics

Penning trap measurement of the magnetic moment of the antiproton

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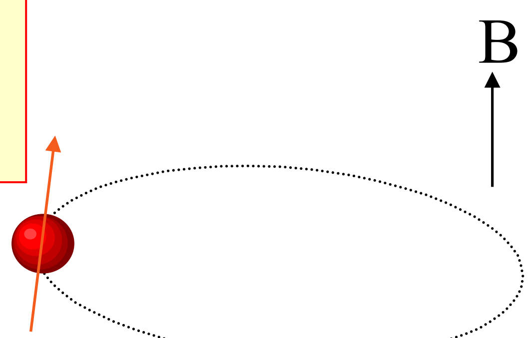
g-Factor of the antiproton

$$\frac{|\overline{\mu}_p|}{\mu_N} = g_p \cdot \frac{|\overline{s}|}{\hbar}$$

μ_p: magnetic moment
g_p: g-factor
s: spin
μ_N: nuclear magneton

proton: $g_p = 2 \times 2.792847337(29)$*
accuracy: 10^{-8}

antiproton: $g_{pbar} = 2 \times 2.800(8)$*
accuracy: 10^{-3}



*Particle Data Group

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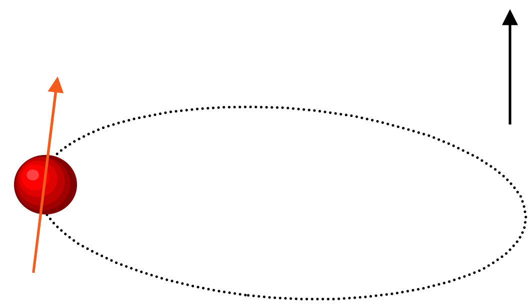
g-Factor of the antiproton

B: magnetic field in Penning trap



Larmor precession frequency:

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

cyclotron frequency:

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

$$g_p = 2 \cdot \frac{\omega_L}{\omega_c}$$

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Geonium: Single electron in a Penning trap

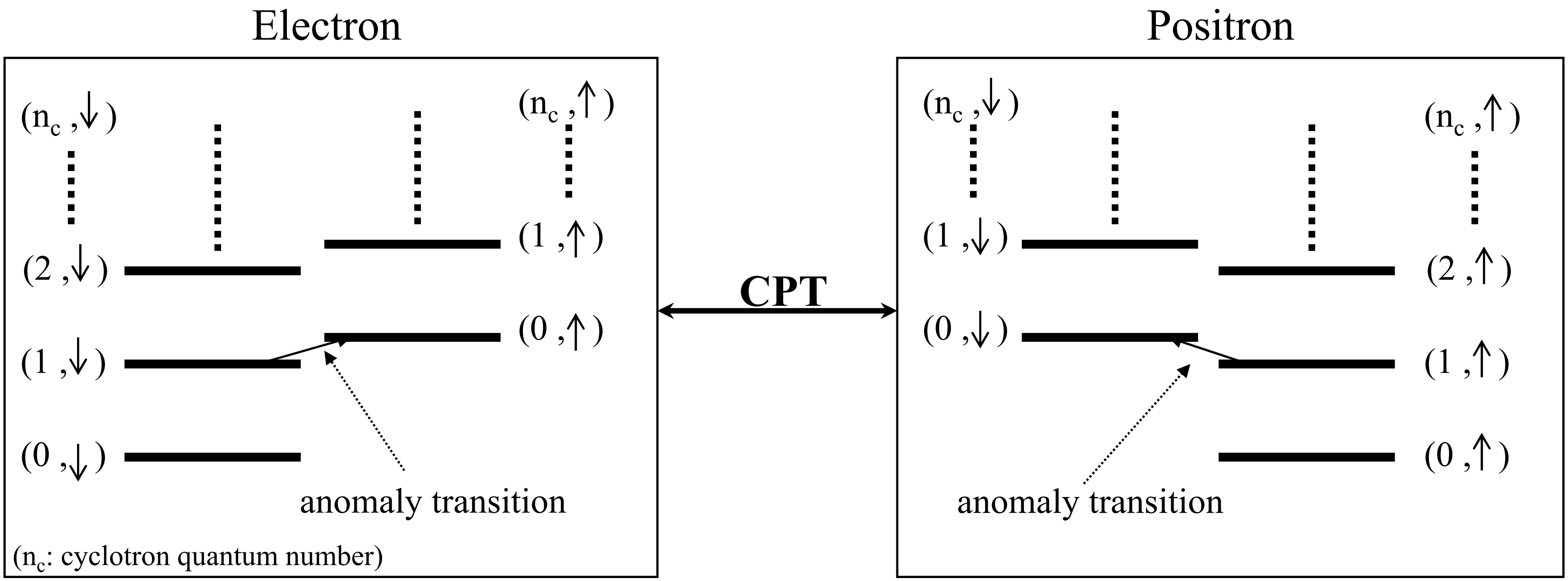

Figure of merit for CPT violation (Bluhm, Kostelecky, Russell):

$$\left|\hbar(\omega_a^+ - \omega_a^-)\right| / 2m_e c^2 \leq 1{,}2\cdot 10^{-21}$$

(Dehmelt, Van Dyck)

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Single antiproton in a Penning trap

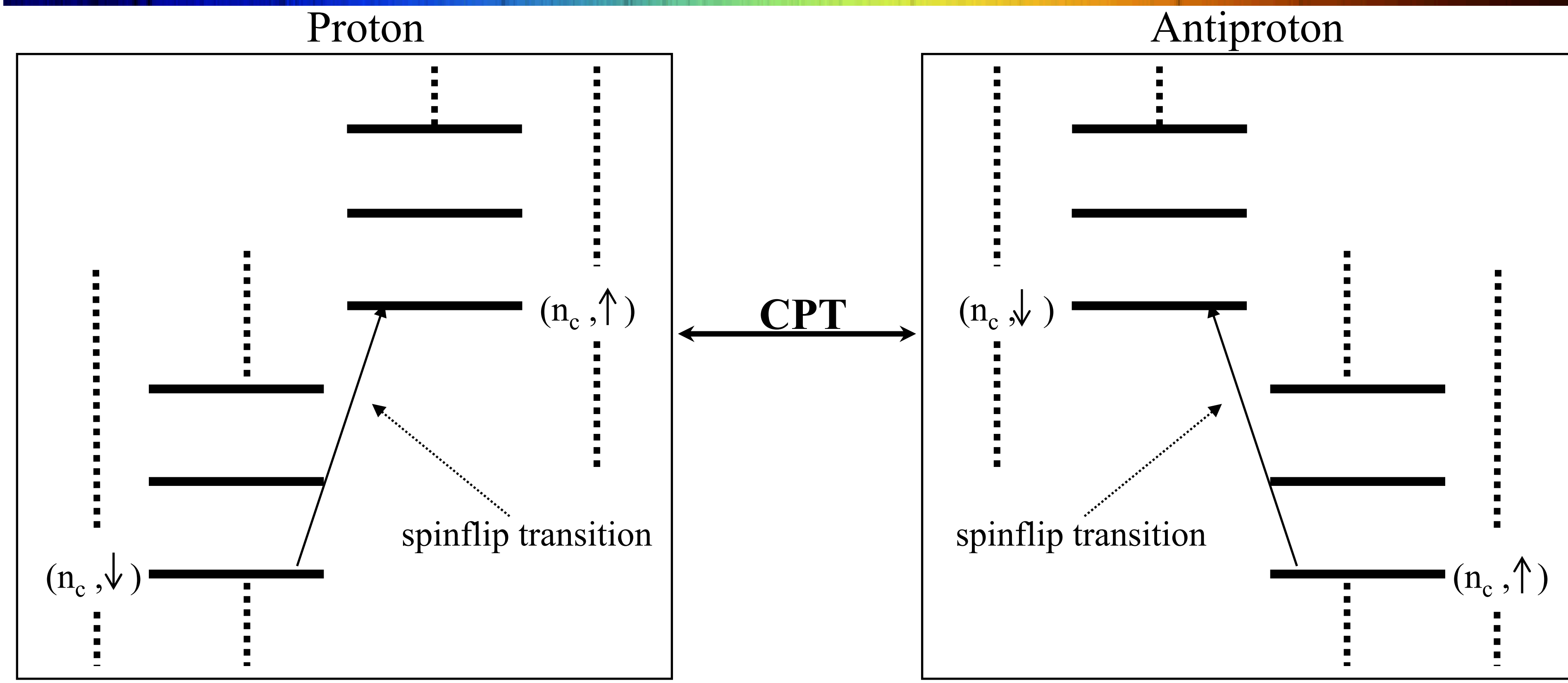


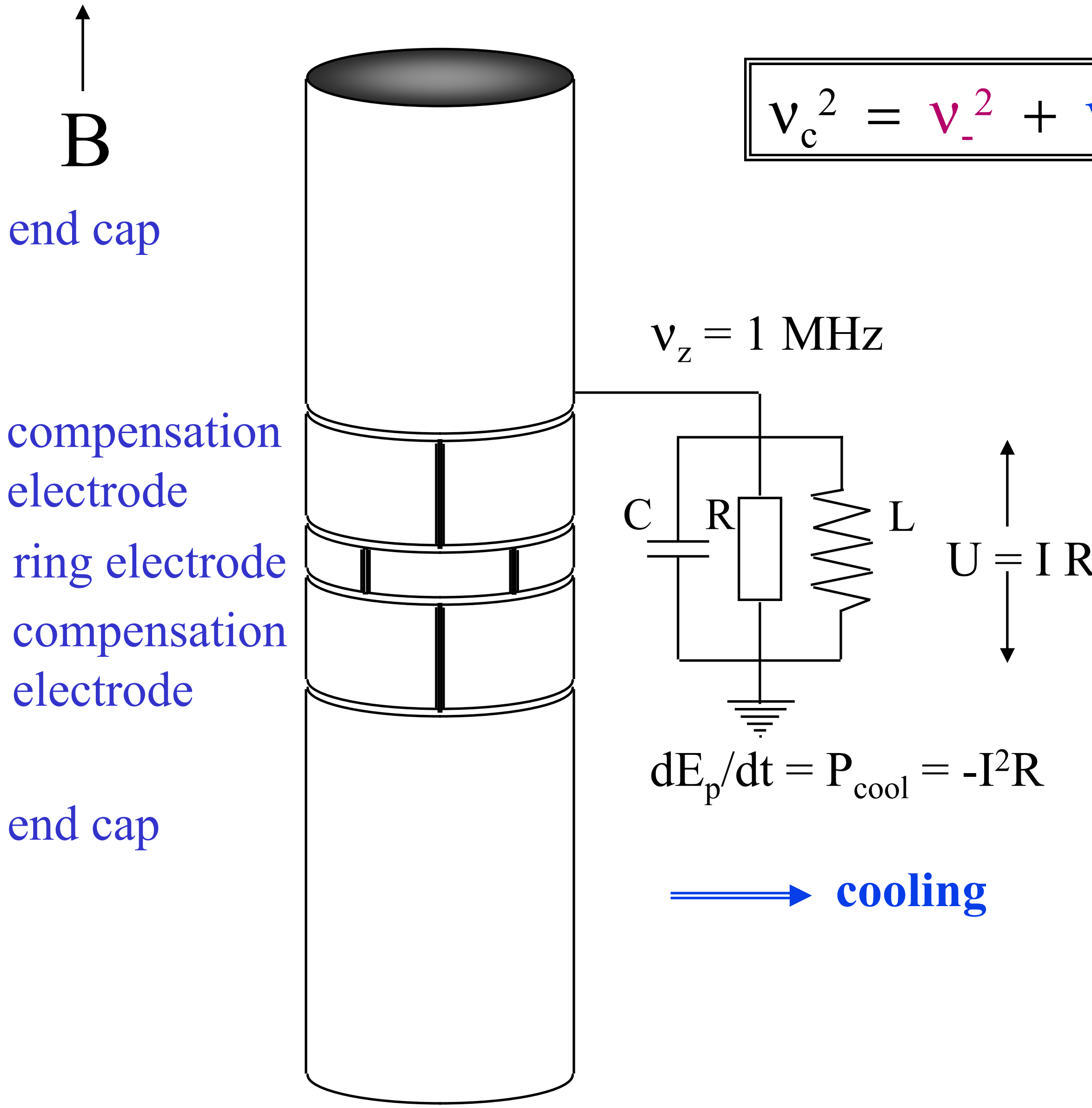
Figure of merit for CPT violation (Bluhm, Kostelecky, Russell):

$$\left|\hbar(\omega_a^+ - \omega_a^-)\right| / 2m_p c^2 \leq 1\cdot 10^{-25}$$

(expected accuracy)

Electronic detection of a single antiproton

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



Cyclotron resonance of a single antiproton

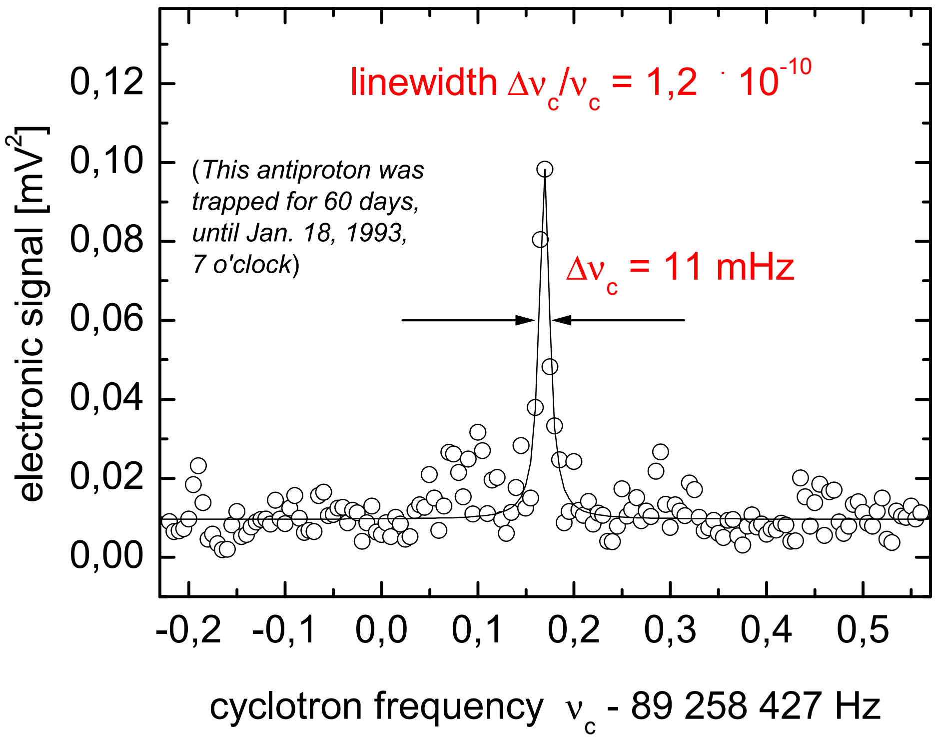
$$\nu_c = \frac{eB}{m\gamma}$$

$\gamma = (1 - ß^2)^{-1/2} = 1{,}000\,000\,005$

relativistic frequency shift:

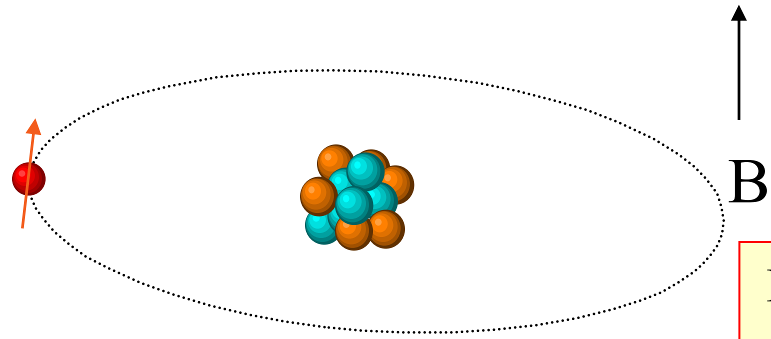
$\Delta\nu_c/\nu_c = - E_c/mc^2$, $E_c = 5$ eV

$\Delta\nu_c = - 0{,}5$ Hz



measured at LEAR, 1993
(G. Gabrielse,
D. Phillips,
W. Quint)

G-Factor of the bound electron in H-like ions



Larmor precession frequency of bound electron:

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

Ion cyclotron frequency:

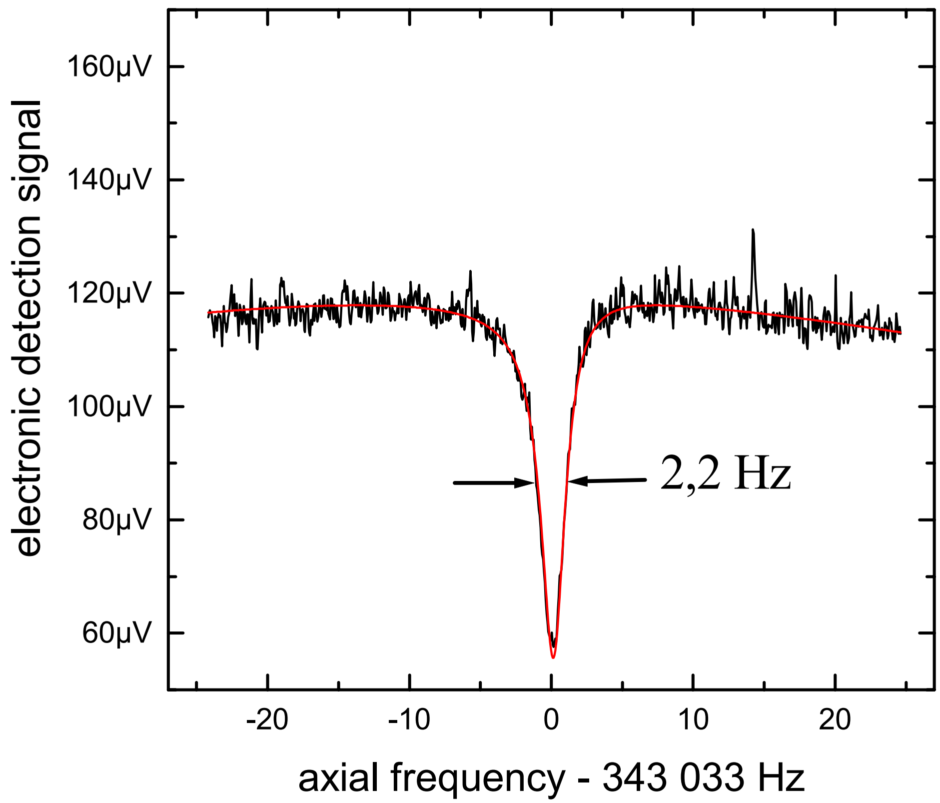
$$\omega_c = \frac{q}{M_{ion}}B$$

$$g_J = 2\cdot\left(\frac{\nu_L}{\nu_c^{ion}}\right)\cdot\frac{\left(m/e\right)^{e}}{\left(M/q\right)^{ion}}$$

new value for the electron mass

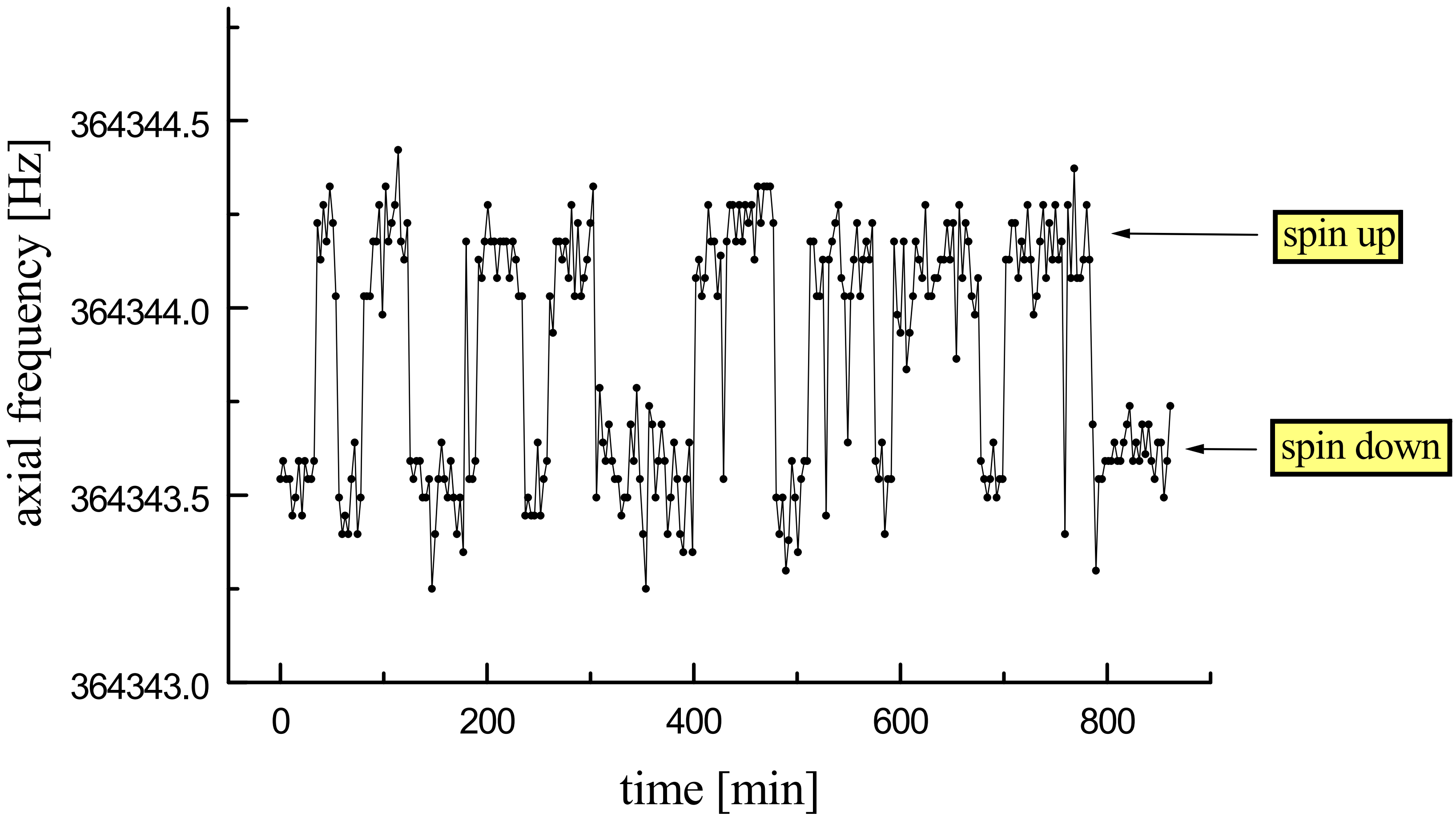
Measurement of the axial frequency of a single C^{5+}-ion

- non-destructive detection at T = 4 Kelvin



Quantum jumps of a single hydrogen-like ion

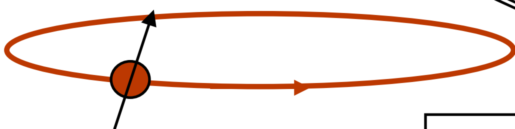
- **Axial frequency depends on spin direction due to continuous Stern-Gerlach effect**



Continuous Stern-Gerlach effect

spin has magnetic moment μ

magnetic bottle: $B(z) = B_0 + B_2 z^2$



↓

magnetic energy: $E_{magn}(z) = \pm\mu B_0 \pm \mu B_2 z^2$

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attractive or repulsive force

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axial frequency = f (spin direction)

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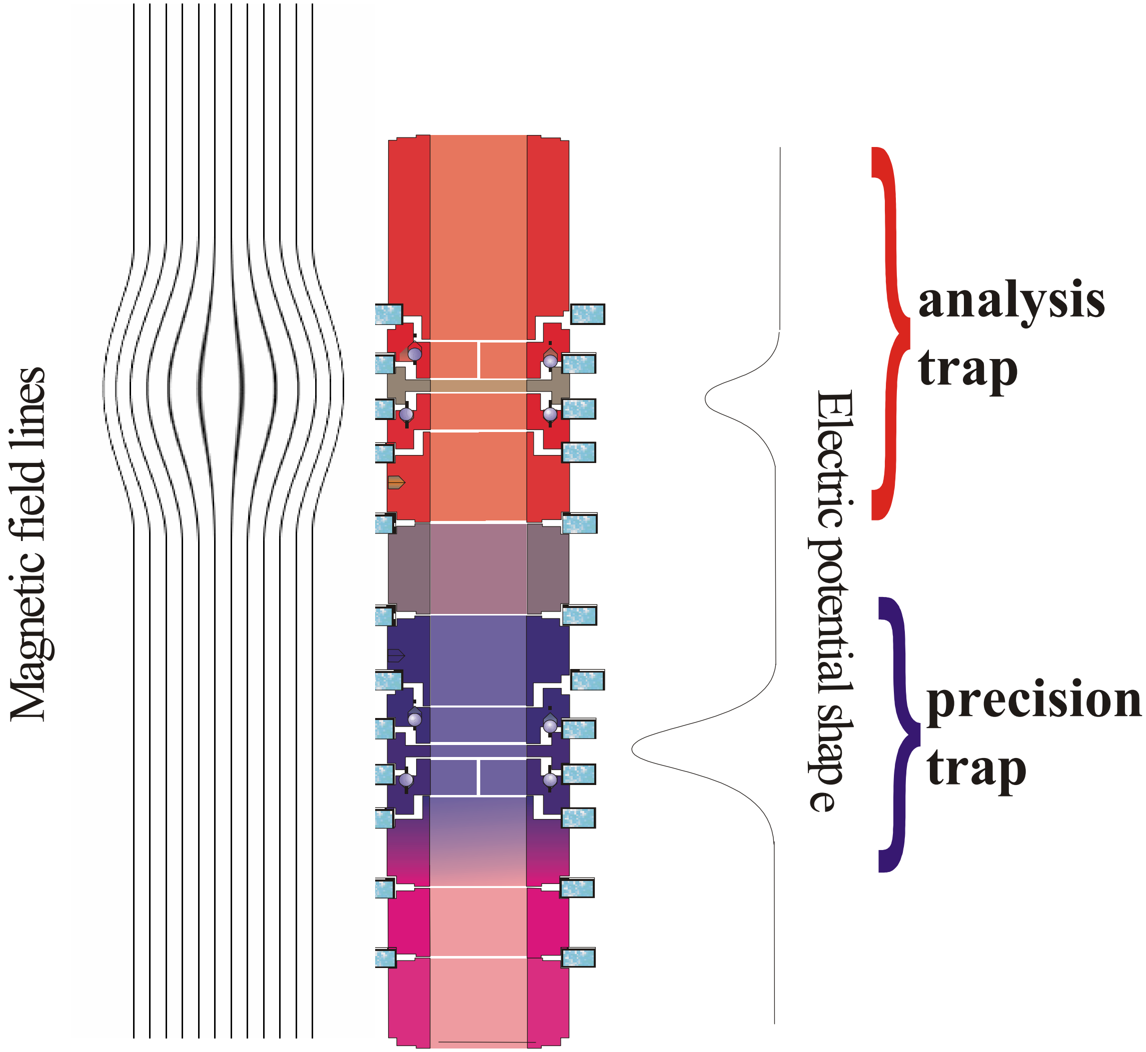
Double-Trap Technique for g-Factor Measurements



Principle:

- **Excitation of spin-flip in precision trap (homogeneous magnetic field)**
- **Detection of spin-flip in analysis trap (inhomogeneous magnetic field for spin-flip detection)**

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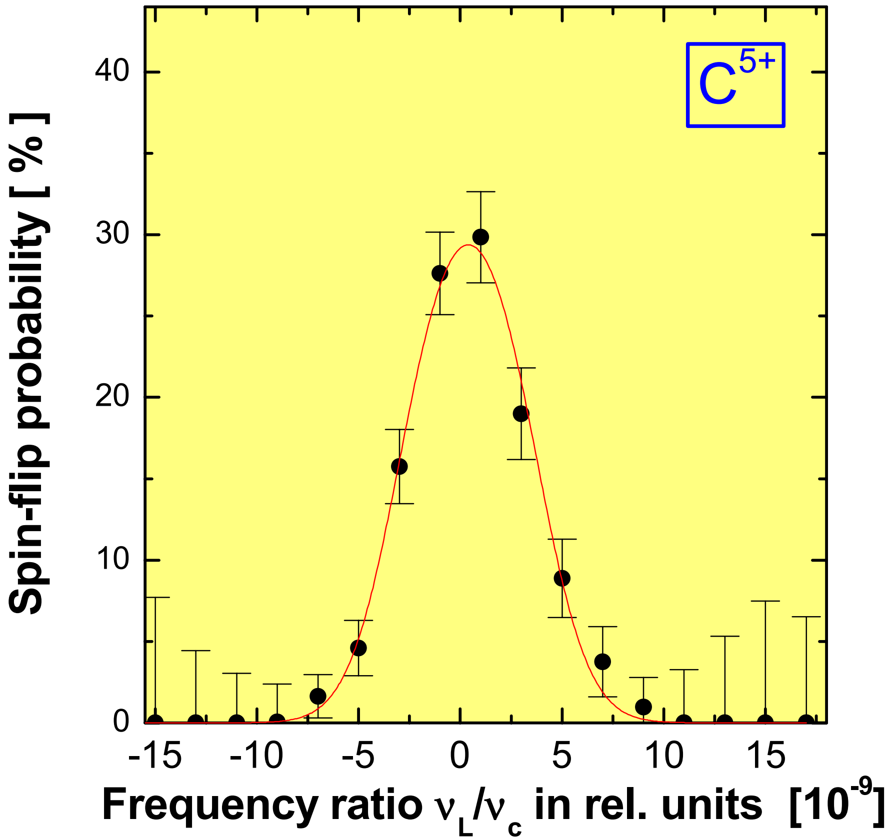
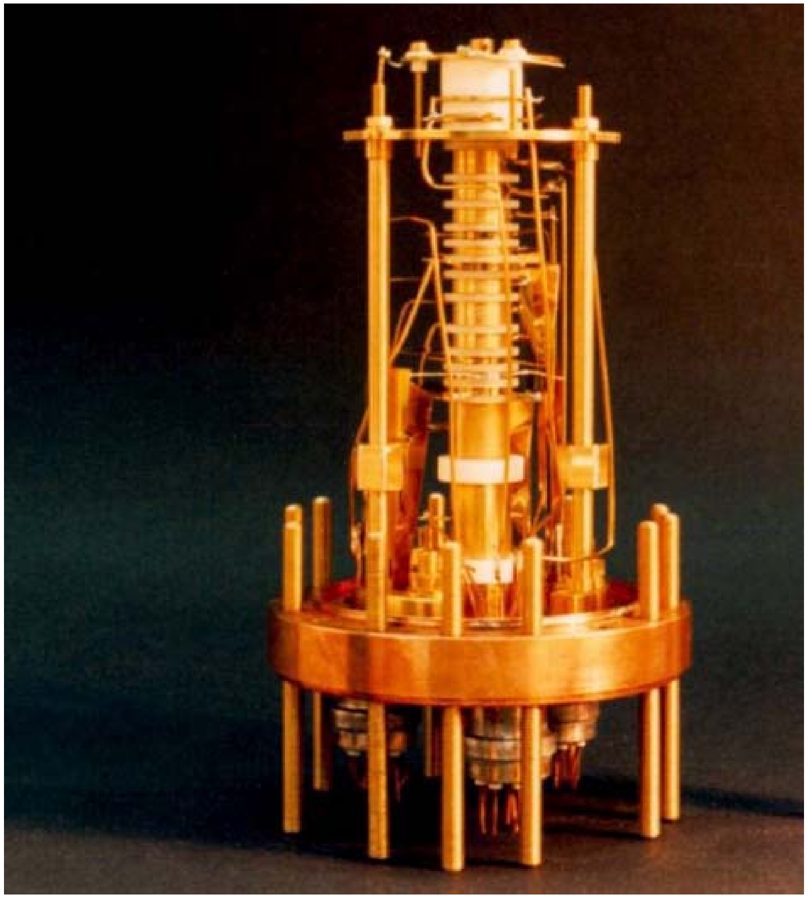
G-Factor of bound electron in highly charged ions

- **Measurement of the g-factor of the bound electron with an accuracy of 7 x 10^{-10}**





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Parameters of g-factor experiments

	Electron (Van Dyck/ Dehmelt)	C^{5+} (Mainz/ GSI)	O^{7+} (Mainz/ GSI)	Antiproton (proposed)
Magnetic moment	$g\mu_B/2$	$g\mu_B/2$	$g\mu_B/2$	$g\mu_N/2$
g-Factor	g = 2.00...	g = 2.00...	g = 2.00...	g = 5.58…
‘Magnetic bottle‘	0.15 mT/mm^2	10 mT/mm^2	10 mT/mm^2	230 mT/mm^2
$\Delta\nu_z$ due to spinflip	1.3 Hz	0.7 Hz	0.46 Hz	0.25 Hz

Conclusions

- Measurement of the magnetic moment of the bound electron with an accuracy of 7×10^{-10}.
- This experimental technique can be employed for the measurement of the magnetic moment of the antiproton.

⇓

Improvement of accuracy in g_{pbar} by six orders of magnitude

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Important test of CPT invariance for baryons