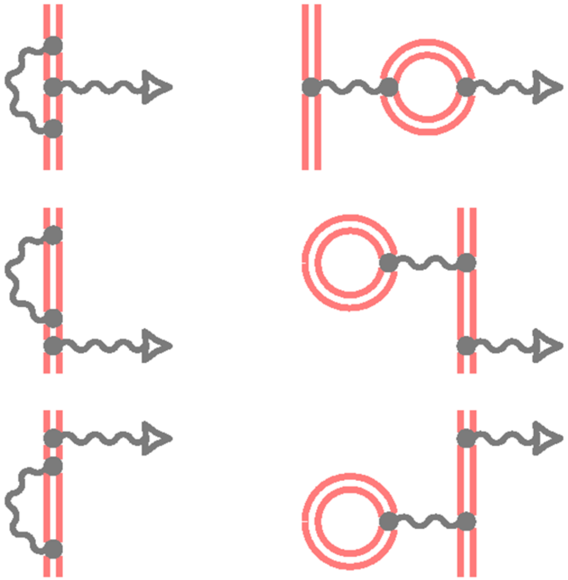
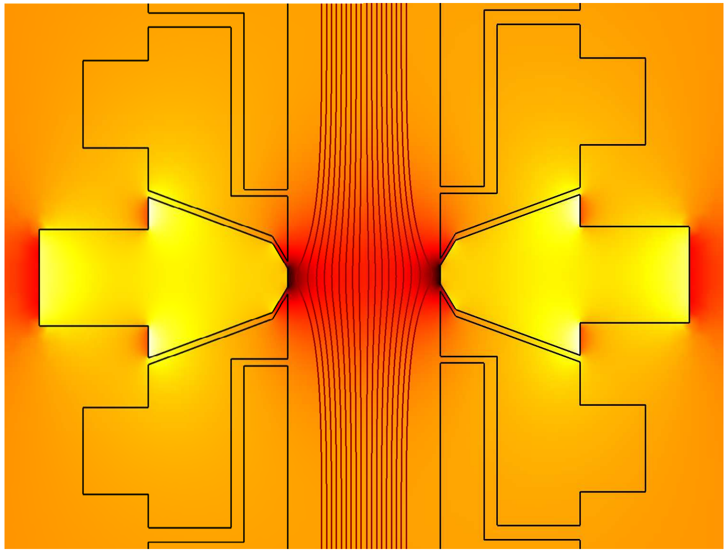
Atomic CPT tests and determination of fundamental parameters of the SM

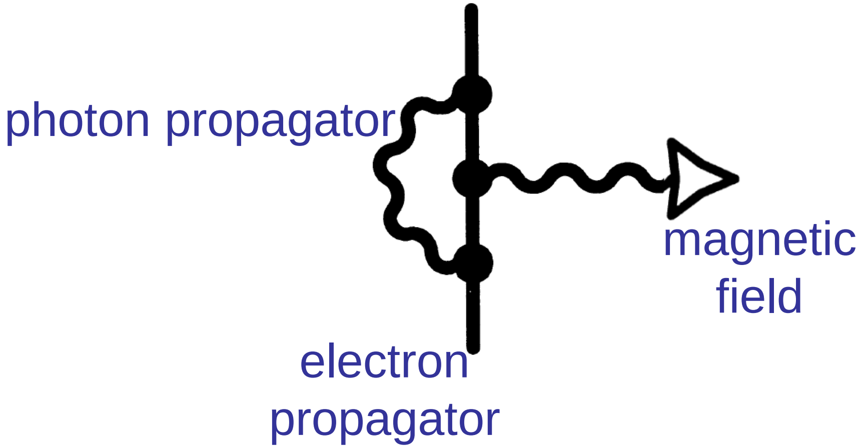




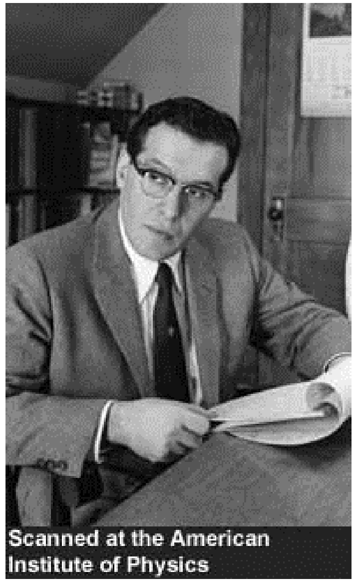
Wolfgang Quint
GSI Darmstadt and Univ. Heidelberg, Germany

QED contributions to the g-factor of the free electron

$$g_{free} = 2\,(1 + C_1\alpha/\pi + C_2(\alpha/\pi)^2 + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + C_5(\alpha/\pi)^5 + \ldots$$



1^{st} order in α:
Schwinger term
$C_1 = ½$



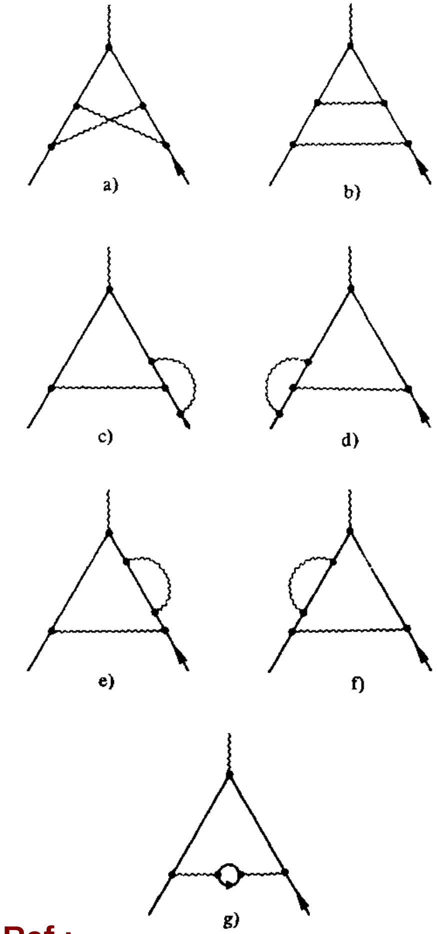
The theory of quantum electrodynamics is, I would say, the jewel of physics - our proudest possession.

R. Feynman

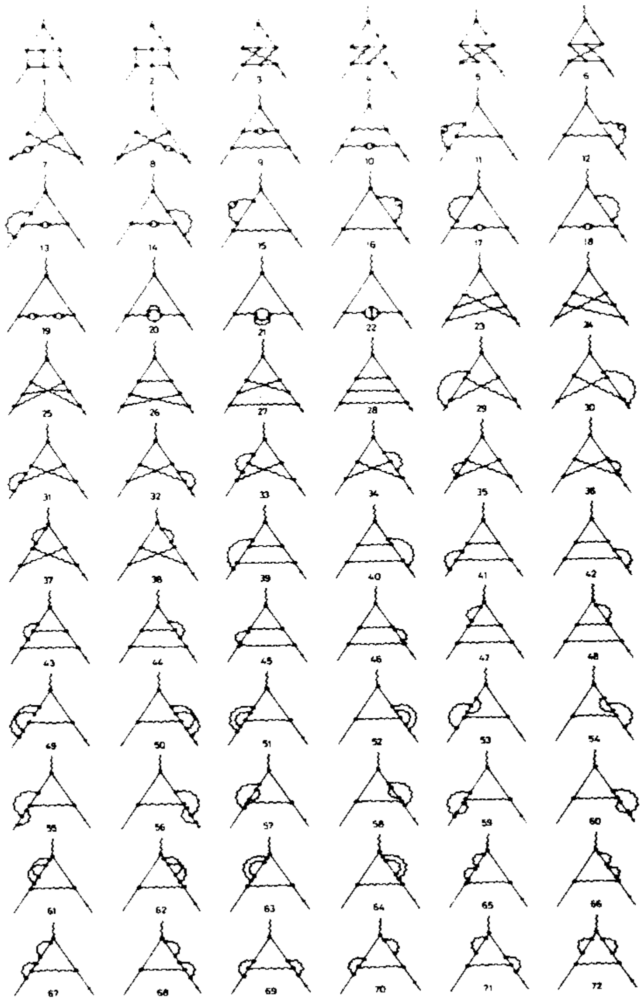
Ref.:
J. Schwinger, Phys. Rev. 73, 416 (1948)

Free electron: QED contributions of 2nd and 3rd order

$$g_{free} = 2\,(1 + C_1\alpha/\pi + C_2(\alpha/\pi)^2 + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + C_5(\alpha/\pi)^5 + \ldots.$$



2nd order in α:
C_2 = - 0.328 478 966
7 graphs



3rd order in α:
C_3 = 1.1765
72 graphs

not shown:
4th order in α:
C_4 = -1.9108
891 graphs

Ref.:
B. Lautrup et al., Phys. Rep. 3, 193 (1972)

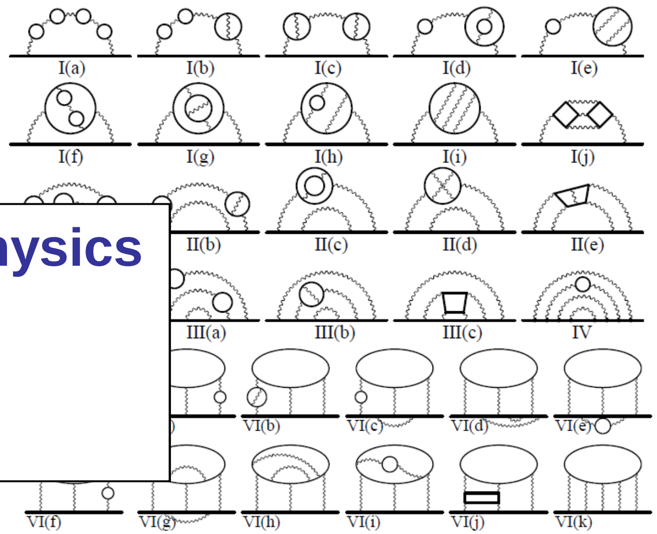
Free electron: QED contributions of 5th order

$$g_{free} = 2\,(1 + C_1\alpha/\pi + C_2(\alpha/\pi)^2 + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + C_5(\alpha/\pi)^5 + ...$$

Harvard g-2 measurement 2011:

g_{free} = 2 (1.001 159 652 180 73 (28)) → determination of α

5th order in α:
C_5 = 9.16
12672 graphs

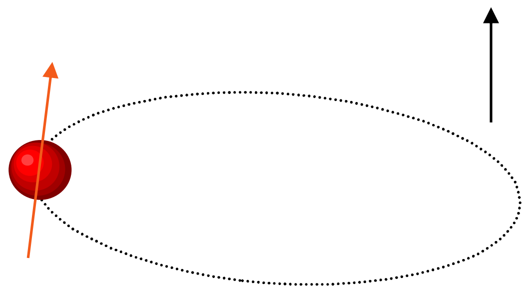


„I am digging at the roots of physics to see whether there is some treasure there.“
Toichiro Kinoshita

Ref.:
Kinoshita et al., arXiv:1205.5368v1 [hep-ph] 24 May 2012

g-Factor of the free electron

B: magnetic field in Penning trap



Larmor precession frequency:

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

cyclotron frequency:

$$\omega_c^e = \frac{e}{m_e}B$$

$$g_e = 2\cdot\frac{\omega_L^e}{\omega_c^e}$$

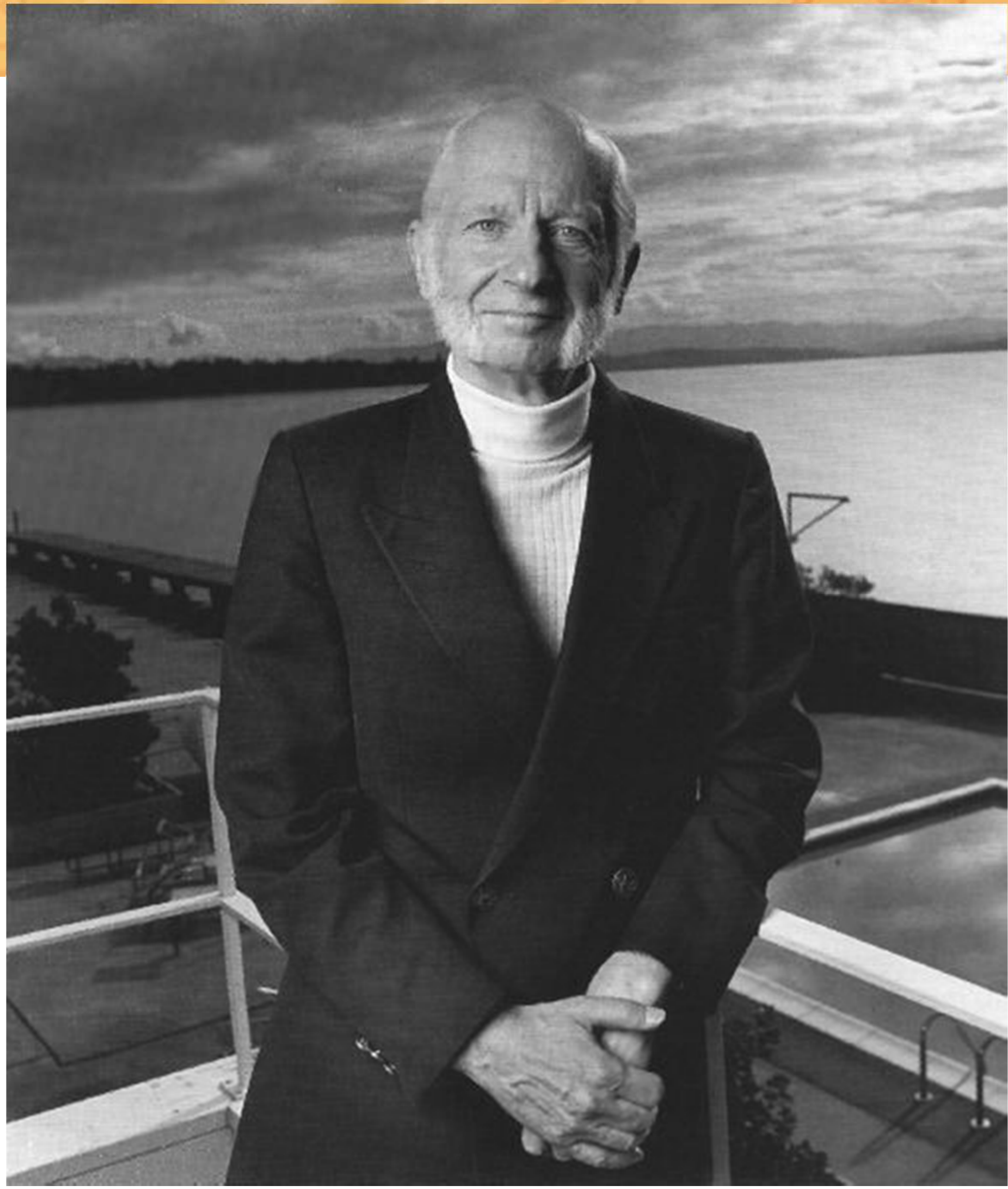
or rather

$$g_e - 2 = 2\cdot\frac{\omega_a^e}{\omega_c^e}$$

(get 3 orders of magnitude in accuracy by Nature)

Hans Dehmelt

Nobel Prize 1989 "for the development of the ion trap technique"



g-Factor of the 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

Electron: g = 2×1.001 159 652 188 4 (43)*

Positron: g = 2×1.001 159 652 187 9 (43)*

*CODATA

PRL 97, 030802 (2006) PHYSICAL REVIEW LETTERS week ending 21 JULY 2006

New Determination of the Fine Structure Constant from the Electron g Value and QED

G. Gabrielse,[1] D. Hanneke,[1] T. Kinoshita,[2] M. Nio,[3] and B. Odom[1,*]

[1]*Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138, USA*

[2]*Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, New York, 14853, USA*

[3]*Theoretical Physics Laboratory, RIKEN, Wako, Saitama, Japan 351-0198*

(Received 17 May 2006; published 17 July 2006)

Quantum electrodynamics (QED) predicts a relationship between the dimensionless magnetic moment of the electron (g) and the fine structure constant (α). A new measurement of g using a one-electron quantum cyclotron, together with a QED calculation involving 891 eighth-order Feynman diagrams, determine $\alpha^{-1} = 137.035\,999\,710\,(96)$ [0.70 ppb]. The uncertainties are 10 times smaller than those of nearest rival methods that include atom-recoil measurements. Comparisons of measured and calculated g test QED most stringently, and set a limit on internal electron structure.

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}, \quad (5)$$

Hadronic and weak contributions to electron g-2

Also owing to the high-precision, non-QED contributions,

$$a(\text{hadron}) = 1.671\,(19) \times 10^{-12},$$
$$a(\text{weak}) = 0.030\,(01) \times 10^{-12}, \quad (12)$$

must be included. Fortunately, these are small and well understood in the context of the standard model [2,7].

B. Krause / Physics Letters B 390 (1997) 392–400

light-by-light

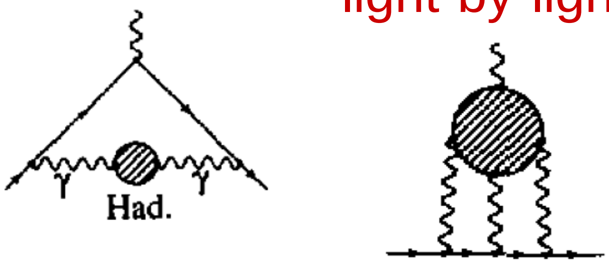
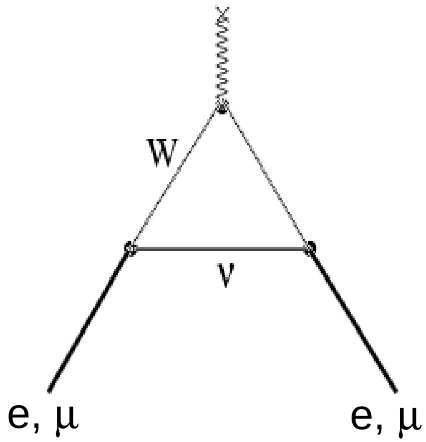
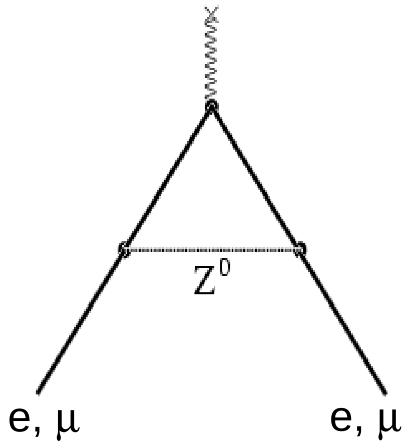


Fig. 1. Leading order hadronic contribution.





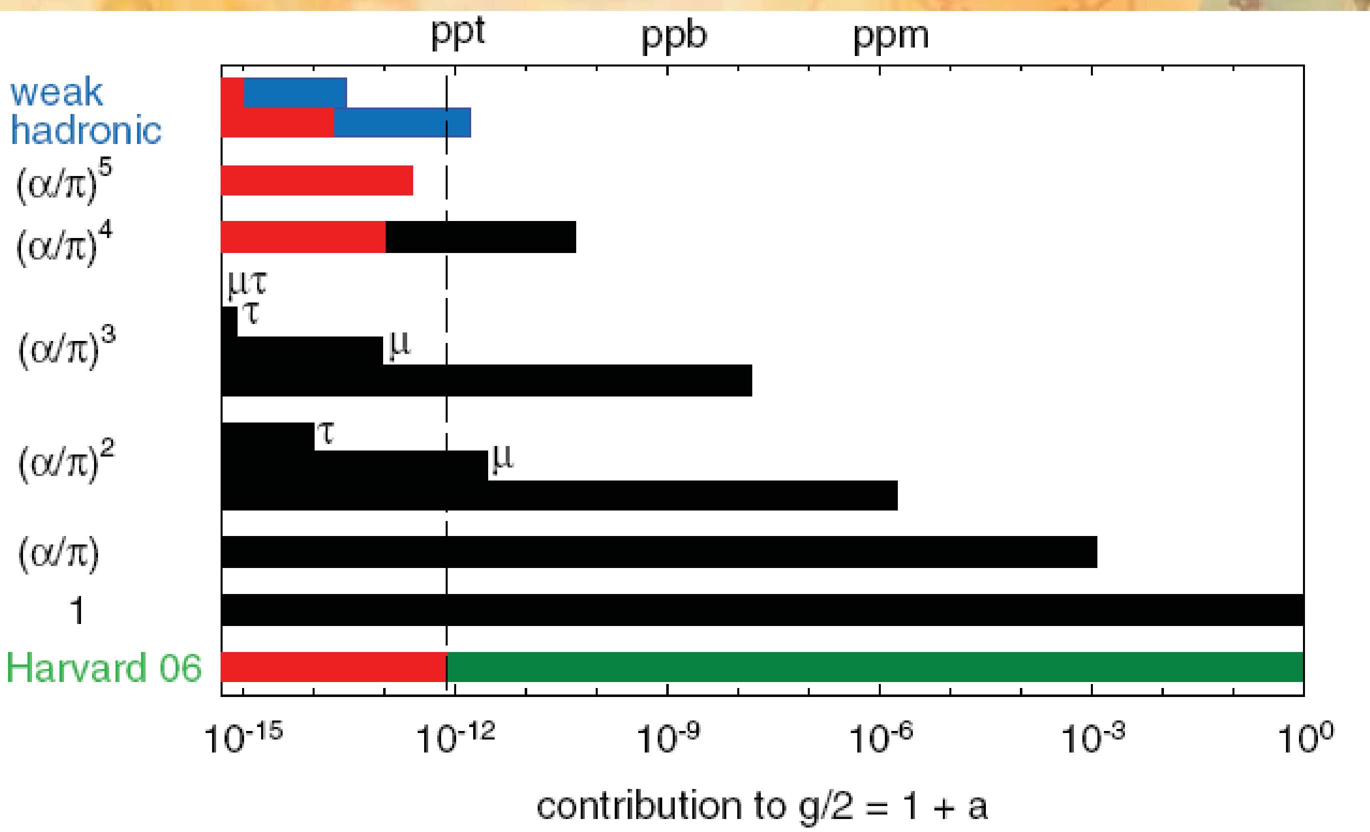


FIG. 2 (color). Contributions to $g/2$ for the experiment (green), terms in the QED series (black), and from short-distance physics (blue). Uncertainties are in red. The μ, τ, and $\mu\tau$ indicate terms dependent on mass ratios m_e/m_μ, m_e/m_τ and the two ratios, m_e/m_μ and m_e/m_τ, respectively.

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

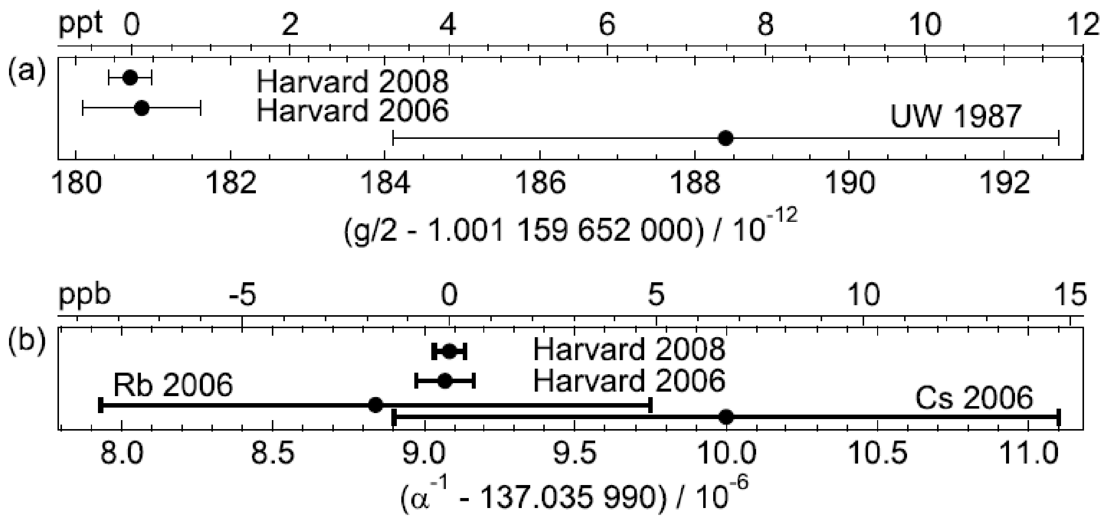


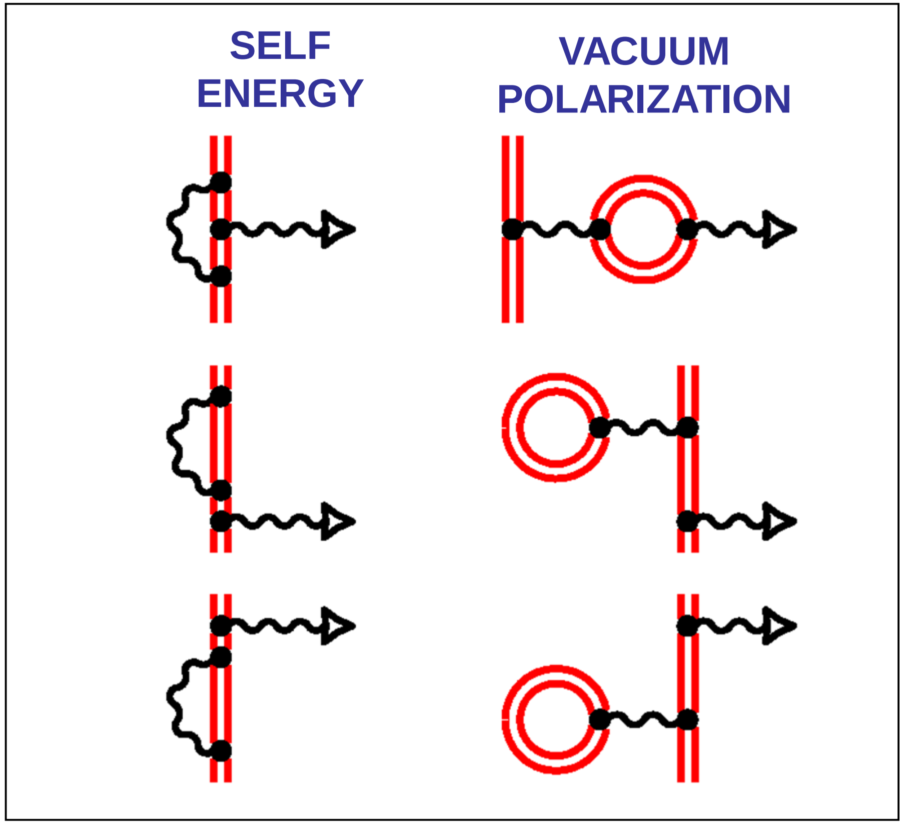
FIG. 1: Most accurate measurements of the electron $g/2$ (a), and most accurate determinations of α (b).

Bound-electron g-factor: Feynman graphs 1st order in α/π

$$g_{bound}/g_{free} \approx 1 - (Z\alpha)^2/3 + \alpha(Z\alpha)^2/4\pi + ...$$

Dirac theory → $(Z\alpha)^2/3$

bound-state QED → $\alpha(Z\alpha)^2/4\pi$

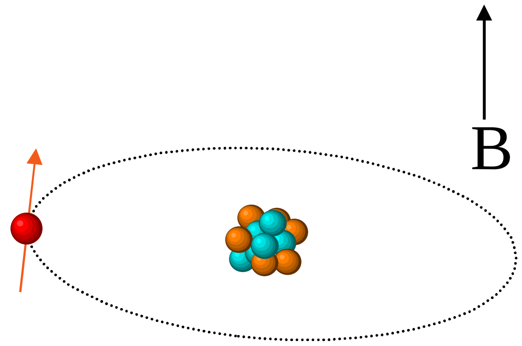


Ref.:
T. Beier, Physics Reports 339, 79 (2000)

g-Factor of the bound electron in a hydrogen-like ion (nucleus has no spin, e.g. $^{12}C^{5+}$, $^{16}O^{7+}$, $^{28}Si^{13+}$, $^{40}Ca^{19+}$)

Larmor precession frequency of the bound electron:

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



Ion cyclotron frequency:

$$\omega_c^{ion} = \frac{Q}{M_{ion}}B$$

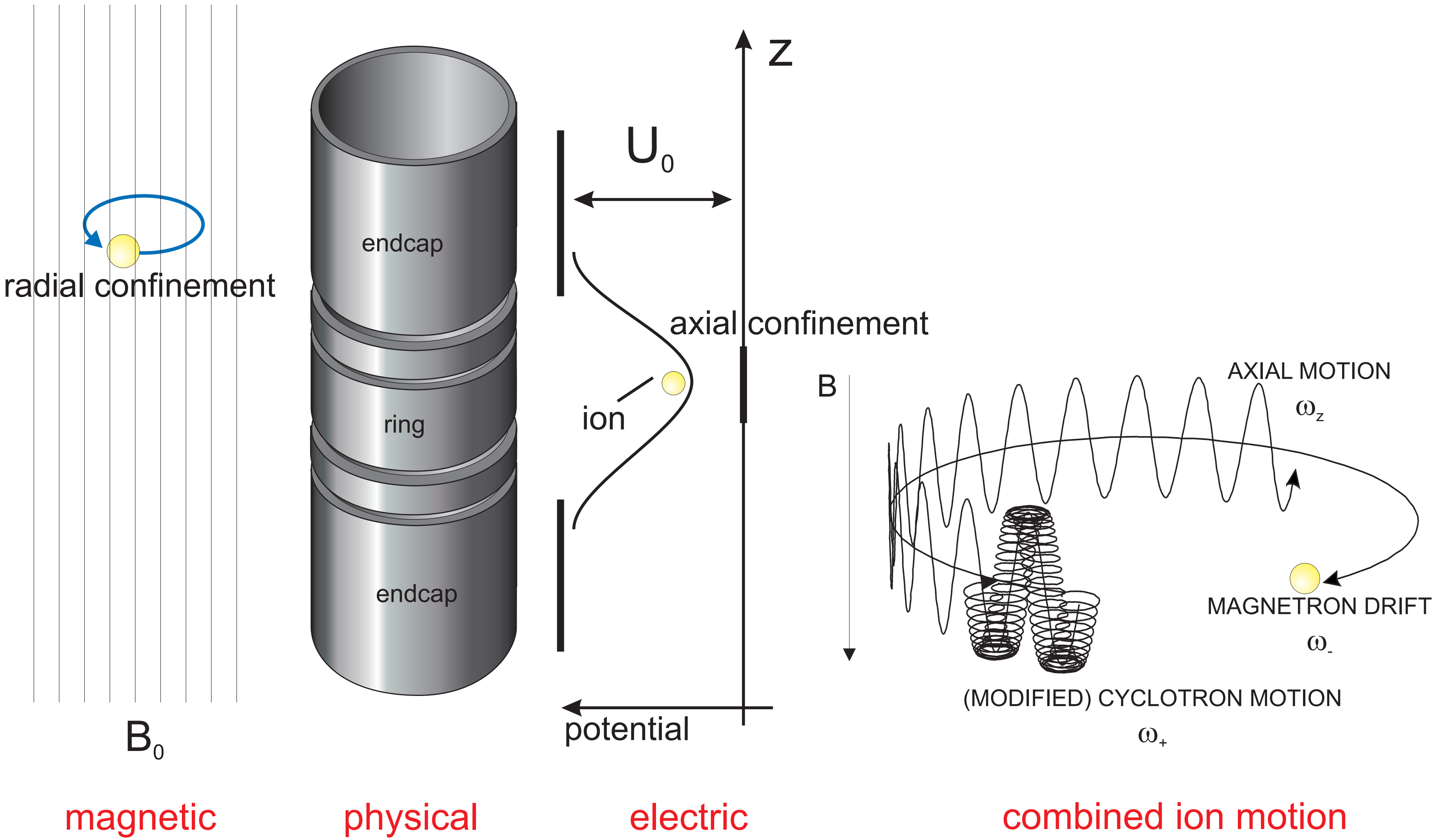
$$g_J = 2\cdot\frac{\omega_L^e}{\omega_c^{ion}}\cdot\frac{m_e}{M_{ion}}\cdot\frac{Q^{ion}}{e}$$

→ 'experimental g-factor'
→ comparison with theory

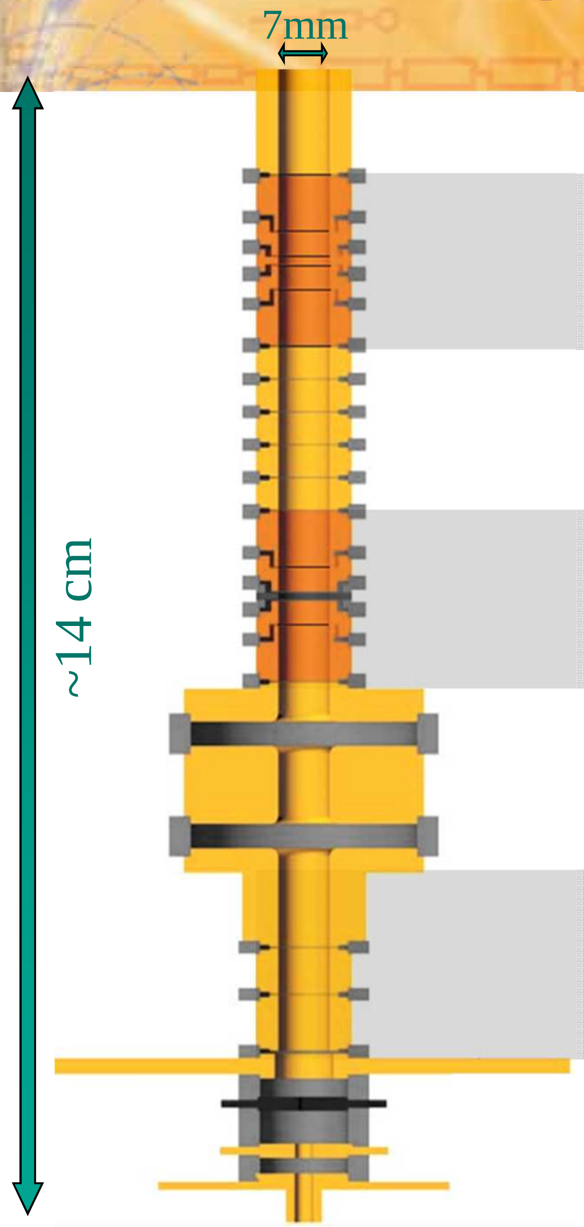
our measurement

external input parameter

A single highly charged ion stored in a Penning trap



Triple Penning trap system



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

Triple Penning trap system

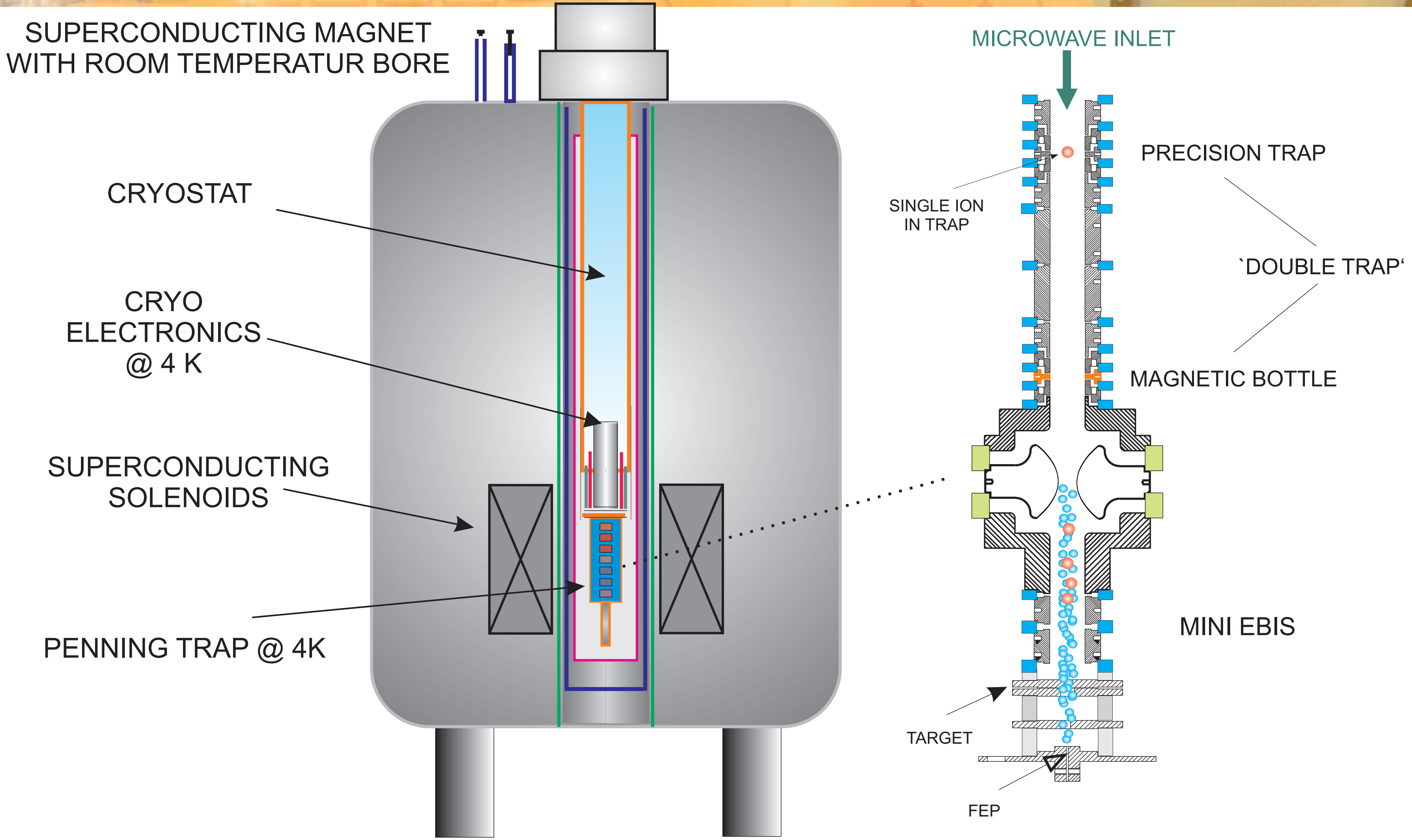
Precision trap (PT)

- Very homogeneous magnetic field

Analysis trap (AT)

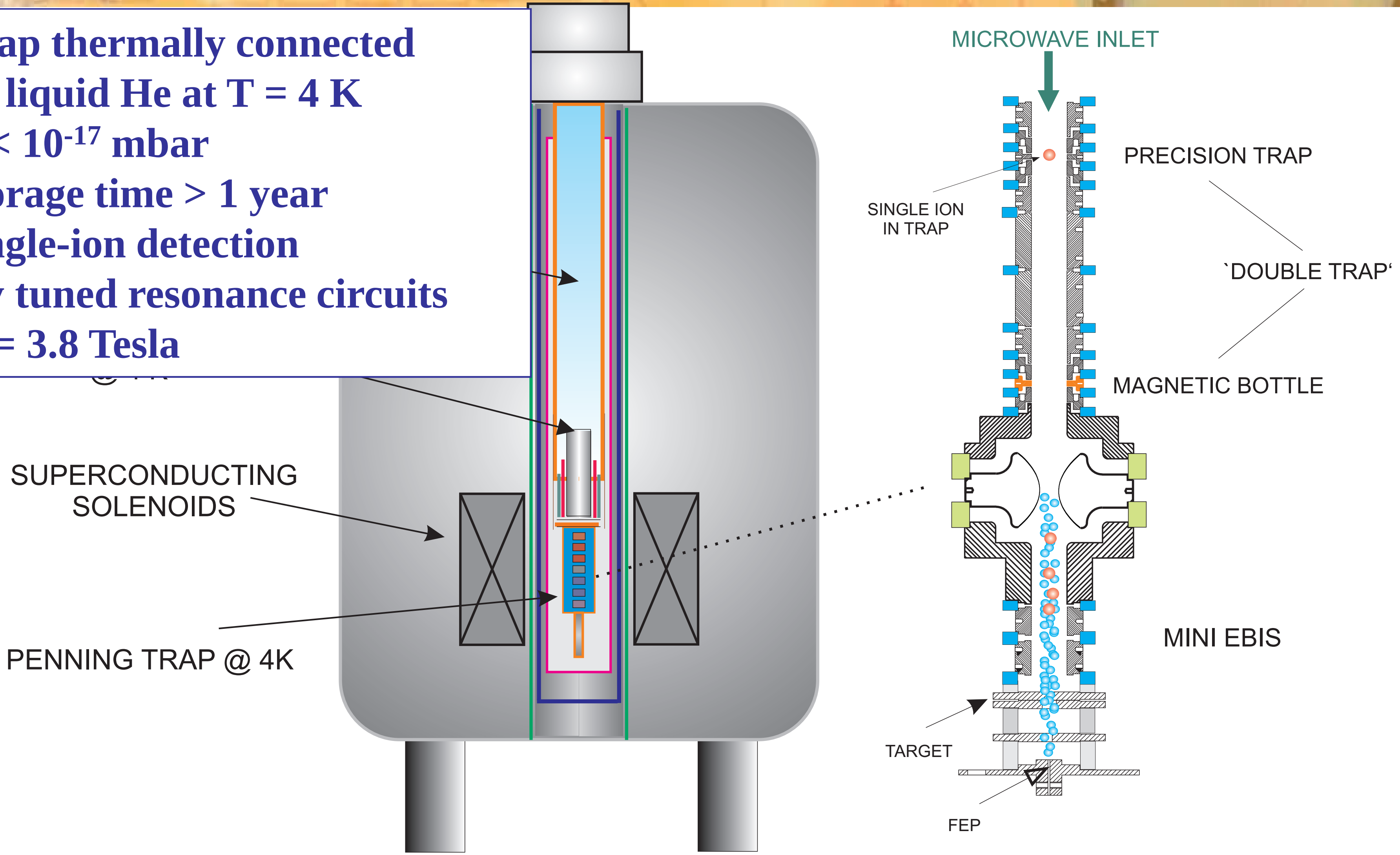
- Magnetic bottle for spin detection

Highly charged ion g-factor apparatus



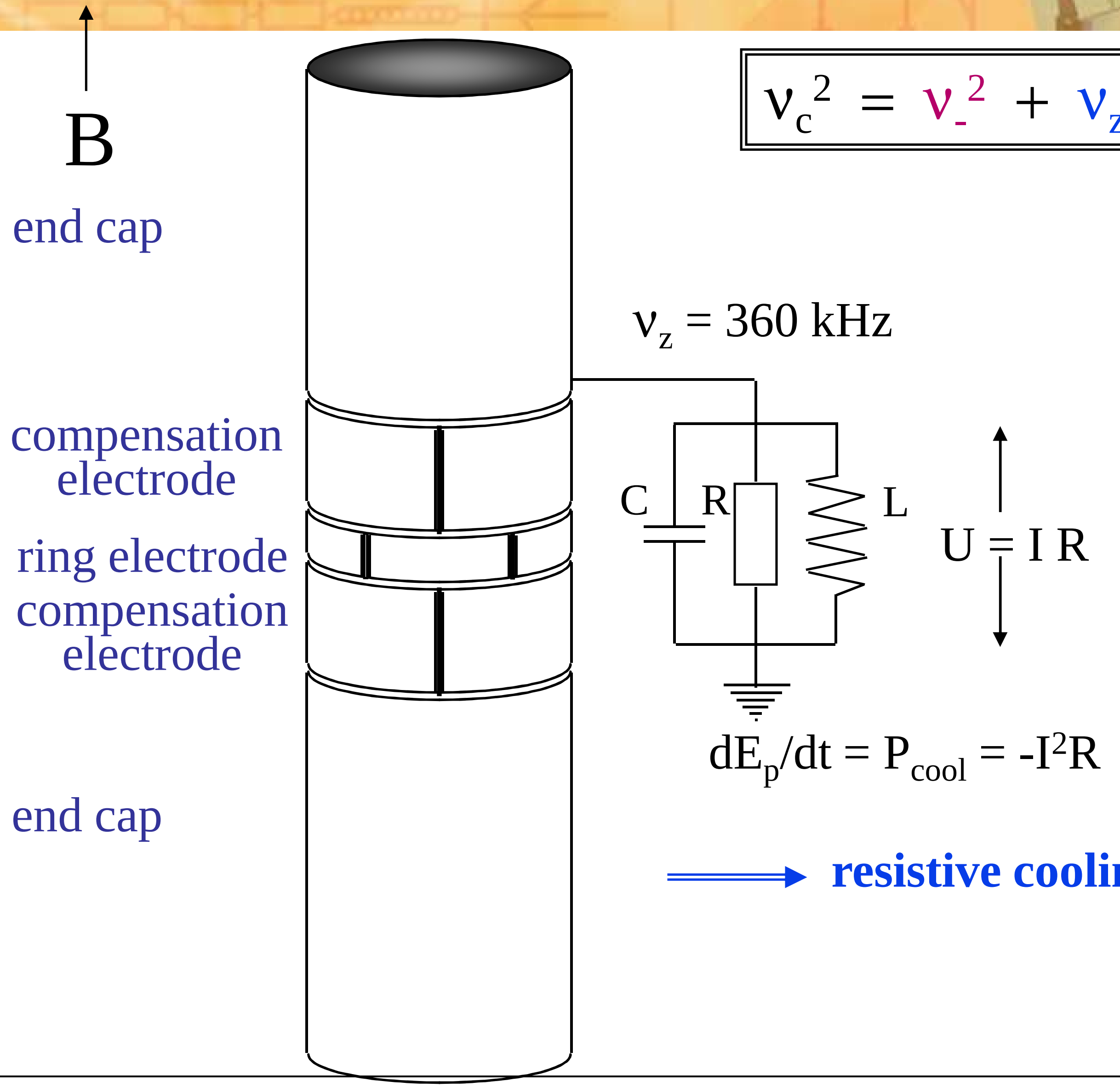
Highly charged ion g-factor apparatus

- Trap thermally connected to liquid He at T = 4 K
- $p < 10^{-17}$ mbar
- storage time > 1 year
- single-ion detection by tuned resonance circuits
- B = 3.8 Tesla



Resistive cooling of trapped ions

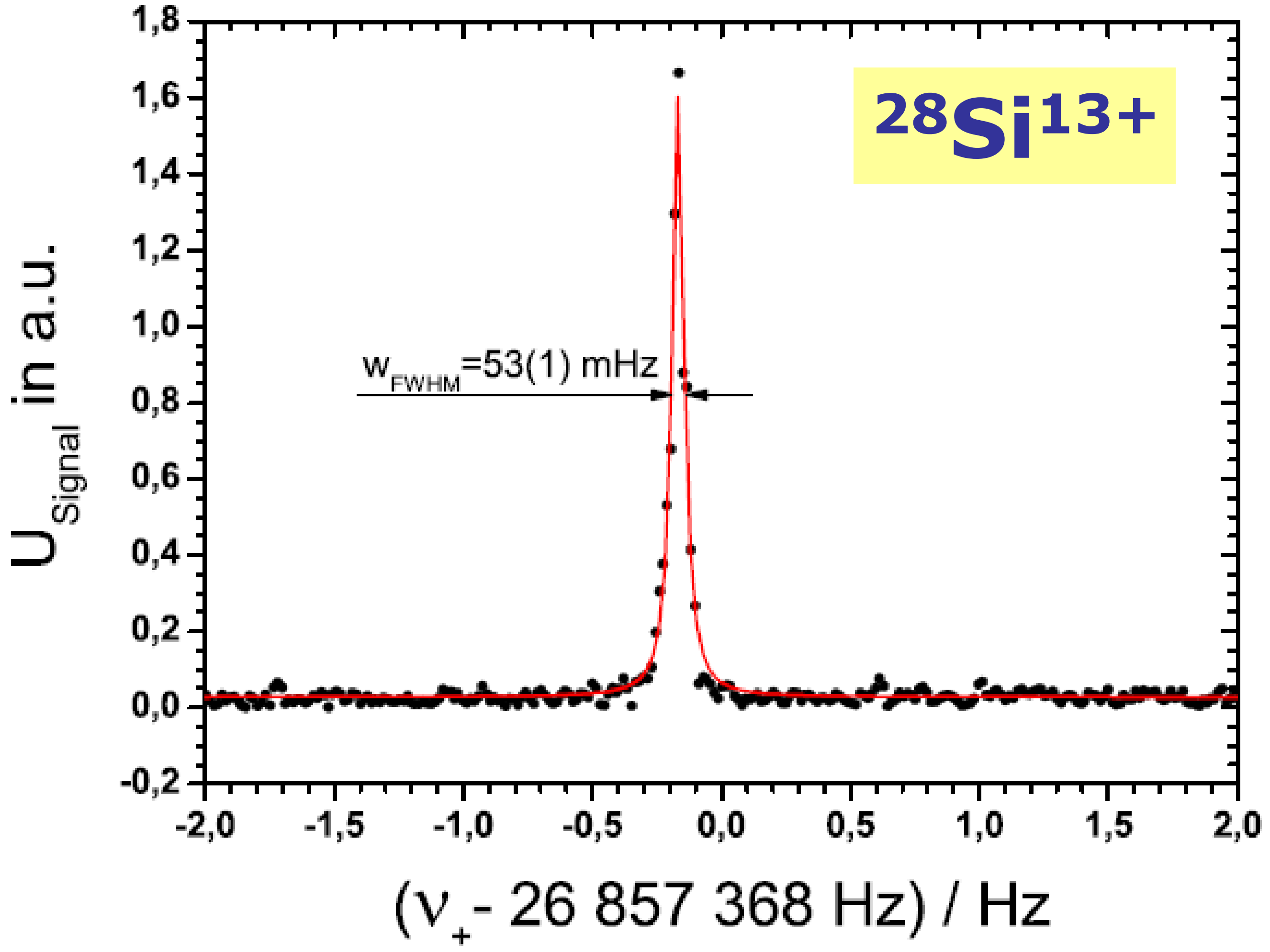
$$\nu_c^2 = \nu_-^2 + \nu_z^2 + \nu_+^2$$



$dE_p/dt = P_{cool} = -I^2R$

→ **resistive cooling**

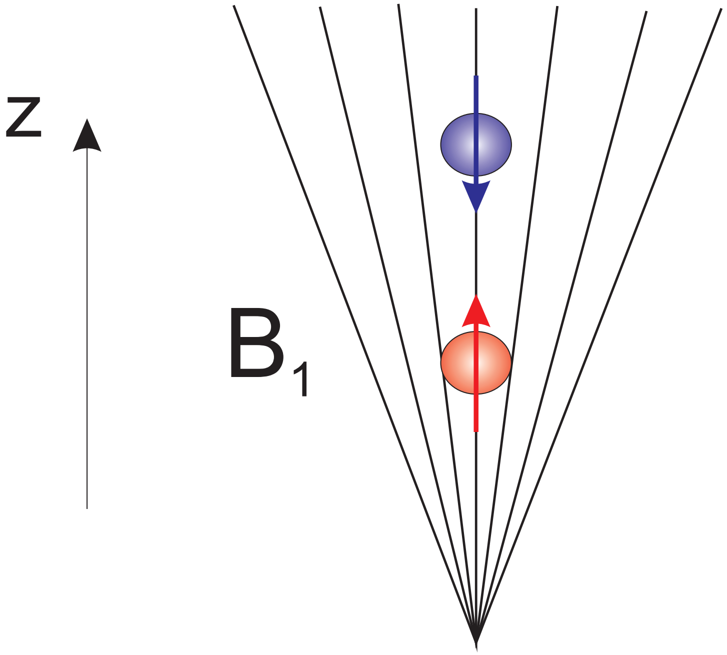
High-resolution cyclotron frequency measurement of a single highly charged silicon ion



Continuous Stern-Gerlach effect: Determination of spin direction

CLASSICAL STERN-GERLACH

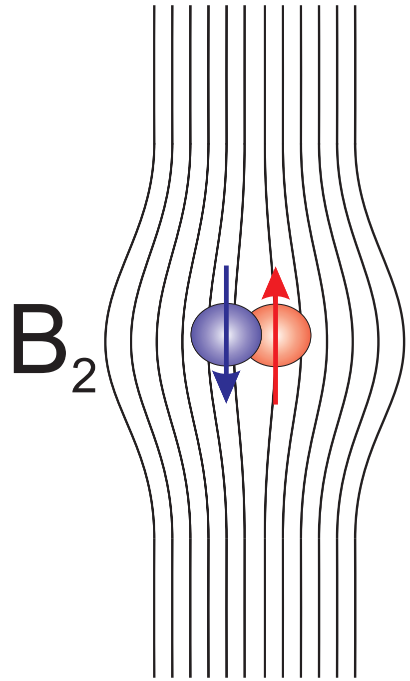
SEPARATION IN POSITION SPACE



$$\Delta z = \frac{\mu L^2}{2KE} B_1$$

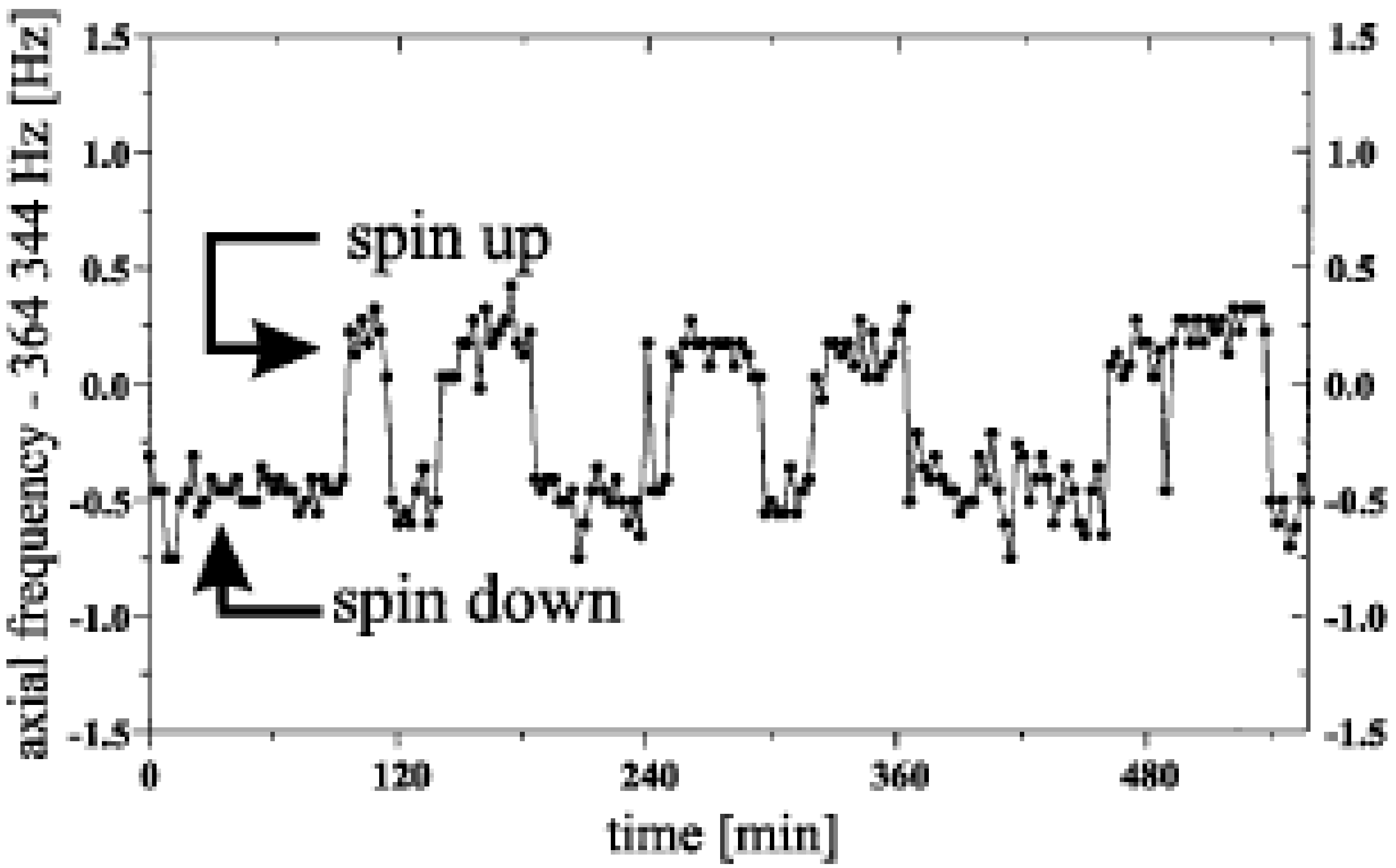
CONTINUOUS STERN-GERLACH

SEPARATION IN FREQUENCY SPACE



$$\Delta \omega_z = \frac{\mu}{m\omega_z} B_2$$

Quantum jump spectroscopy:
Spin-flip transitions in the analysis trap



Bound electron magnetic moment measurement on hydrogen-like silicon $^{28}Si^{13+}$

PRL **107**, 023002 (2011) PHYSICAL REVIEW LETTERS week ending 8 JULY 2011

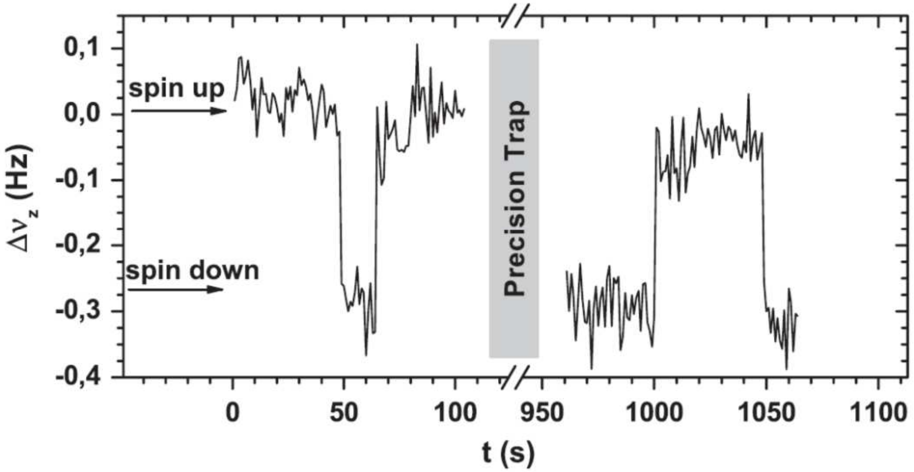
g Factor of Hydrogenlike $^{28}Si^{13+}$

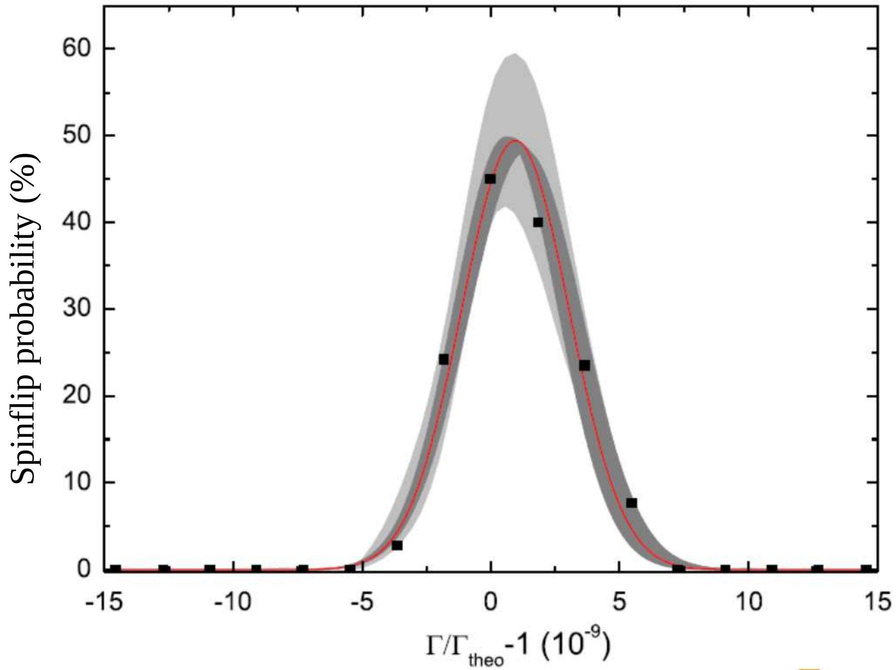
S. Sturm,[1,2] A. Wagner,[1] B. Schabinger,[1,2] J. Zatorski,[1] Z. Harman,[1,3] W. Quint,[4] G. Werth,[2] C. H. Keitel,[1] and K. Blaum[1]

[1]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[2]*Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany*
[3]*ExtreMe Matter Institute EMMI, Planckstraße 1, 64291 Darmstadt, Germany*
[4]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany*

(Received 6 May 2011; published 7 July 2011)

We determined the experimental value of the *g* factor of the electron bound in hydrogenlike $^{28}Si^{13+}$ by using a single ion confined in a cylindrical Penning trap. From the ratio of the ion's cyclotron frequency and the induced spin flip frequency, we obtain $g = 1.995\,348\,958\,7(5)(3)(8)$. It is in excellent agreement with the state-of-the-art theoretical value of 1.995 348 958 0(17), which includes QED contributions up to the two-loop level of the order of $(Z\alpha)^2$ and $(Z\alpha)^4$ and represents a stringent test of bound-state quantum electrodynamics calculations.





Comparison of theory and experiment: g-Factor of the bound electron in H-like carbon $^{12}C^{5+}$, oxygen $^{16}O^{7+}$ and silicon $^{28}Si^{13+}$

$g_J(^{12}C^{5+})$ = 2.001 041 590 18 (3) theoretical value
$g_J(^{12}C^{5+})$ = 2.001 041 596 4 (10)(44) our measurement

$g_J(^{16}O^{7+})$ = 2.000 047 020 32 (11) theoretical value
$g_J(^{16}O^{7+})$ = 2.000 047 025 4 (15)(44) our measurement

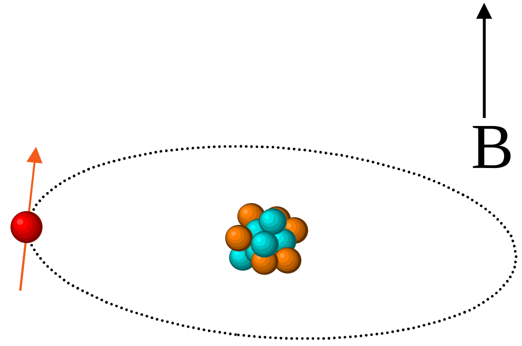
$g_J(^{28}Si^{13+})$ = 1.995 348 958 0 (17) theoretical value
$g_J(^{28}Si^{13+})$ = 1.995 348 958 7 (5)(3)(8) our measurement

Lit.:
T. Beier et al., PRL 88, 011603 (2002)
V. Shabaev et al., PRL 88, 091801 (2002)
V. Yerokhin et al., PRL 89, 143001 (2002)
K. Pachucki, V. Yerokhin et al., PRA 72, 022108 (2005)
S. Sturm et al., PRL 107, 023002 (2011)

Electron mass in atomic mass units u

Larmor precession frequency of the bound electron:

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



Ion cyclotron frequency:

$$\omega_c^{ion} = \frac{Q}{M_{ion}}B$$

$$\frac{m_e}{M_{ion}} = \frac{g_J}{2}\cdot\frac{\omega_c^{ion}}{\omega_L^{e}}\cdot\frac{e}{Q}$$

→ determination of electron mass

theory as input parameter

our measure-ment

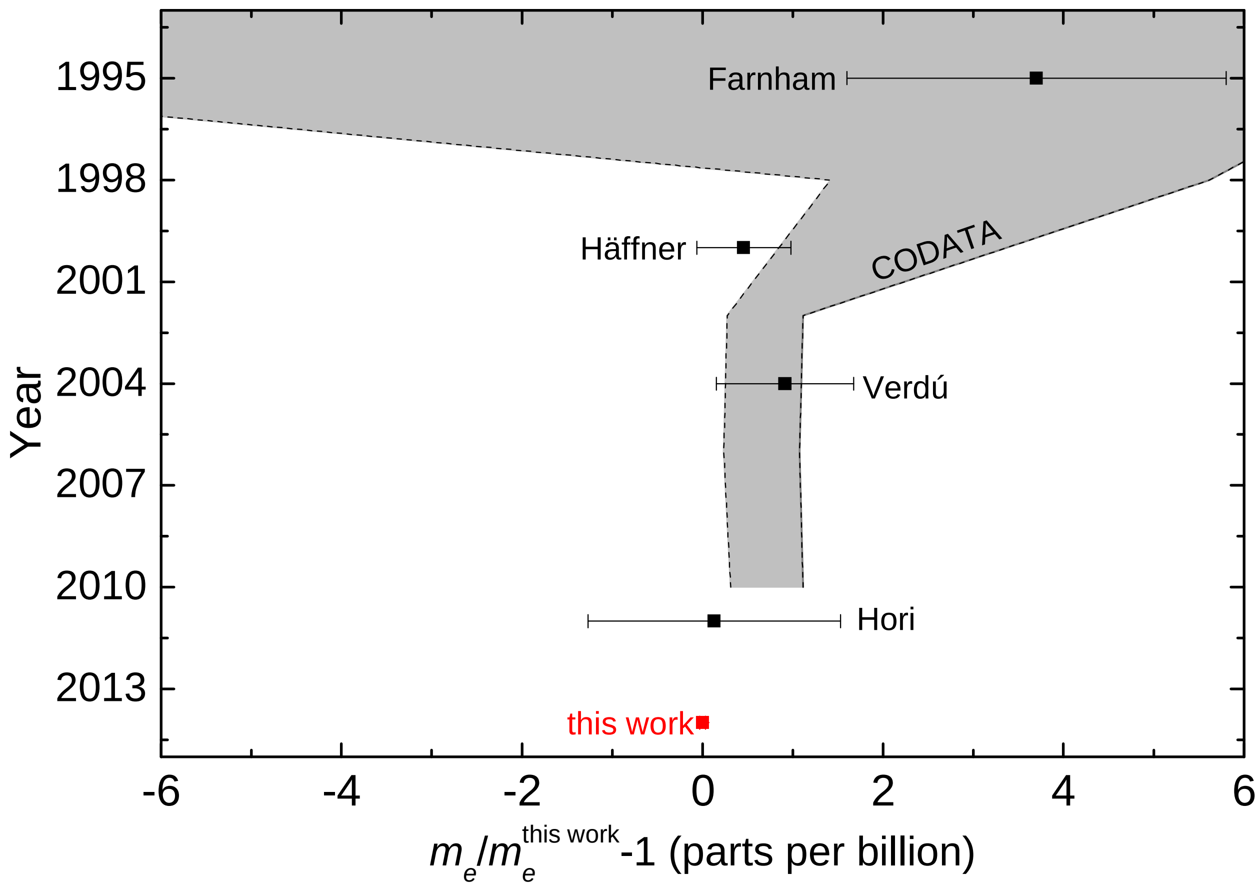
m_e=0,000 548 579 909 067 (14)(9)(2) u

[S. Sturm et al., Nature 506, 467-470 (2014)]

(stat)(syst)(theo)

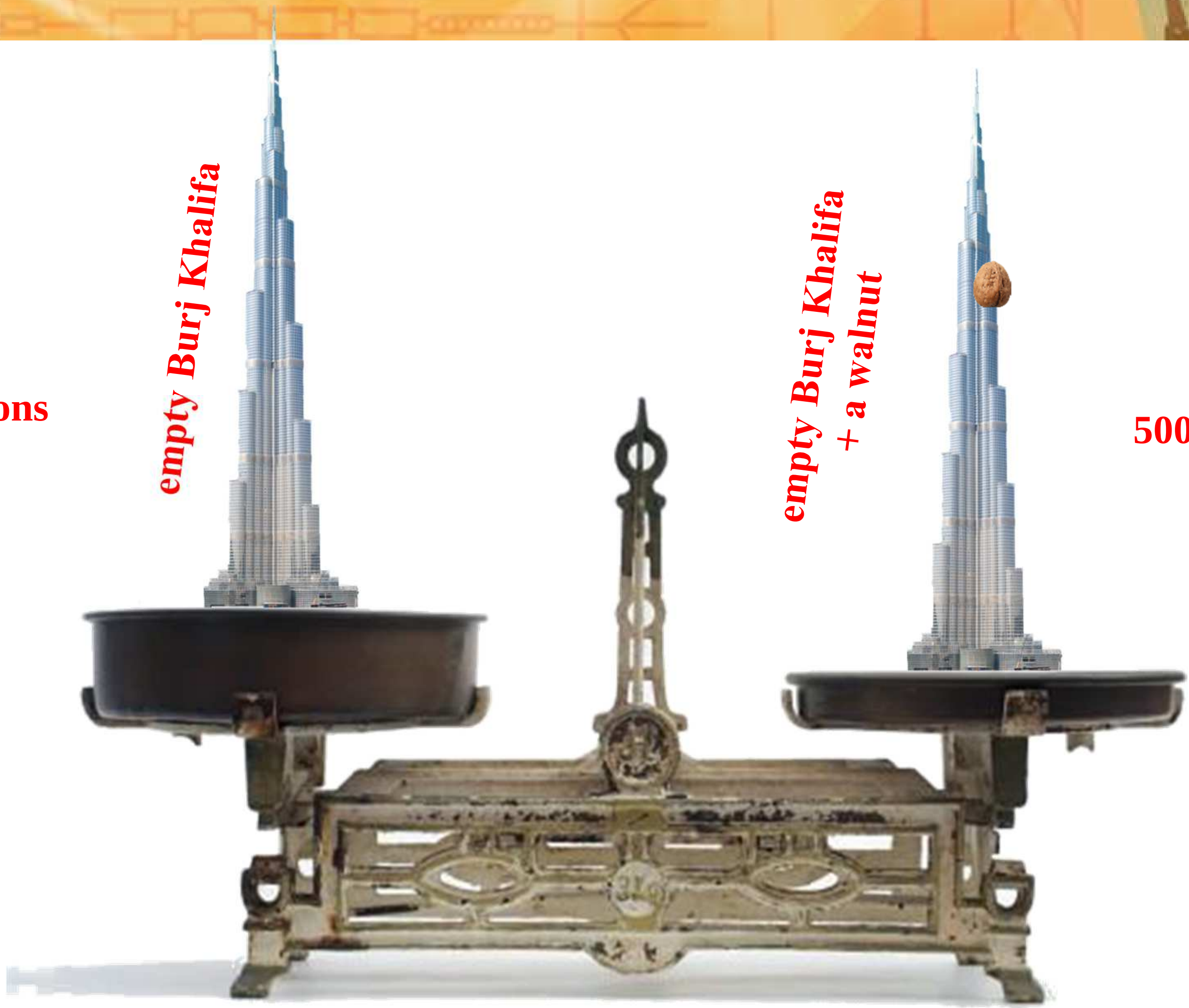
$\delta m_e/m_e = 3\cdot10^{-11}$

History of electron mass measurements



Who has forgotten the walnut?

500000 tons



500000.000015 tons

Relative Precision: $3 \cdot 10^{-11}$

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]

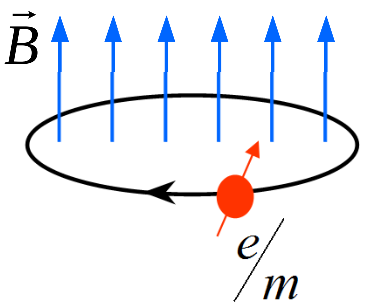
$$\omega_c = \frac{e}{m_p} B$$

Cyclotron frequency

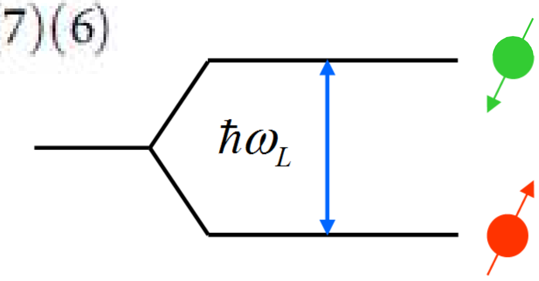
$$g = 2\frac{\omega_L}{\omega_c}$$

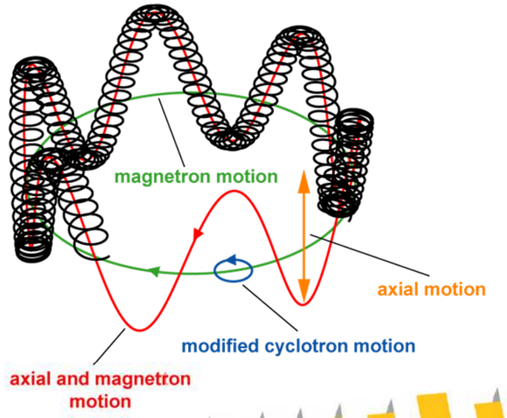
$$\omega_L = g\frac{e}{2m_p} B$$

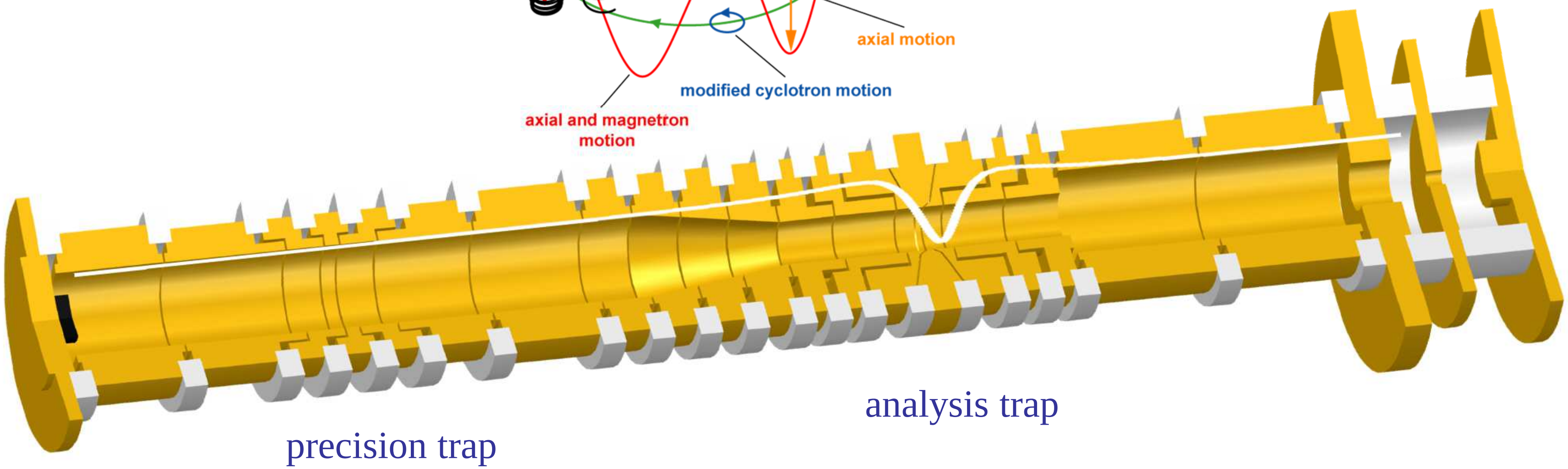
Larmor frequency



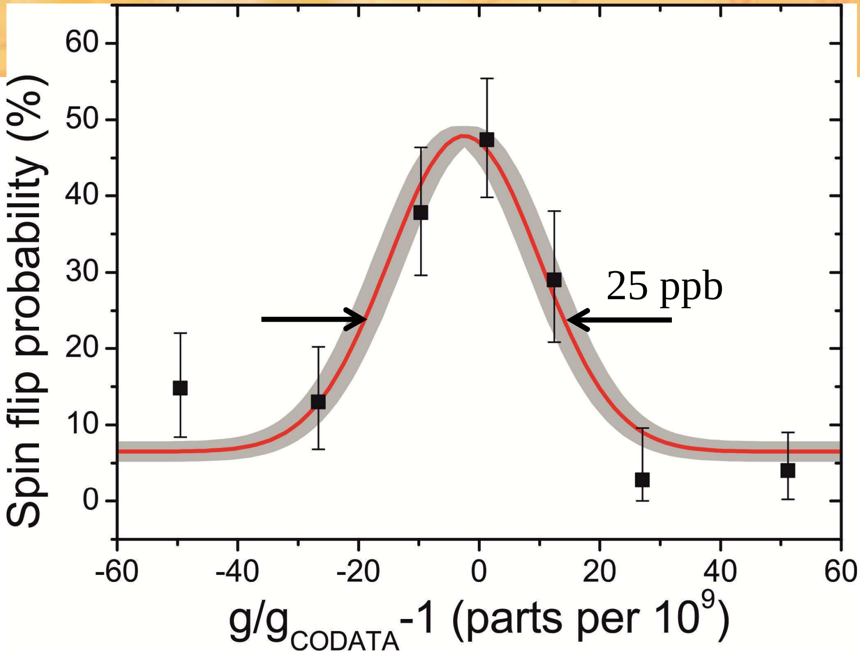
$$\frac{\mu_p}{\mu_N} = \frac{g_p}{2} = 2.792\,847\,350(7)(6)$$







The g-factor of the proton

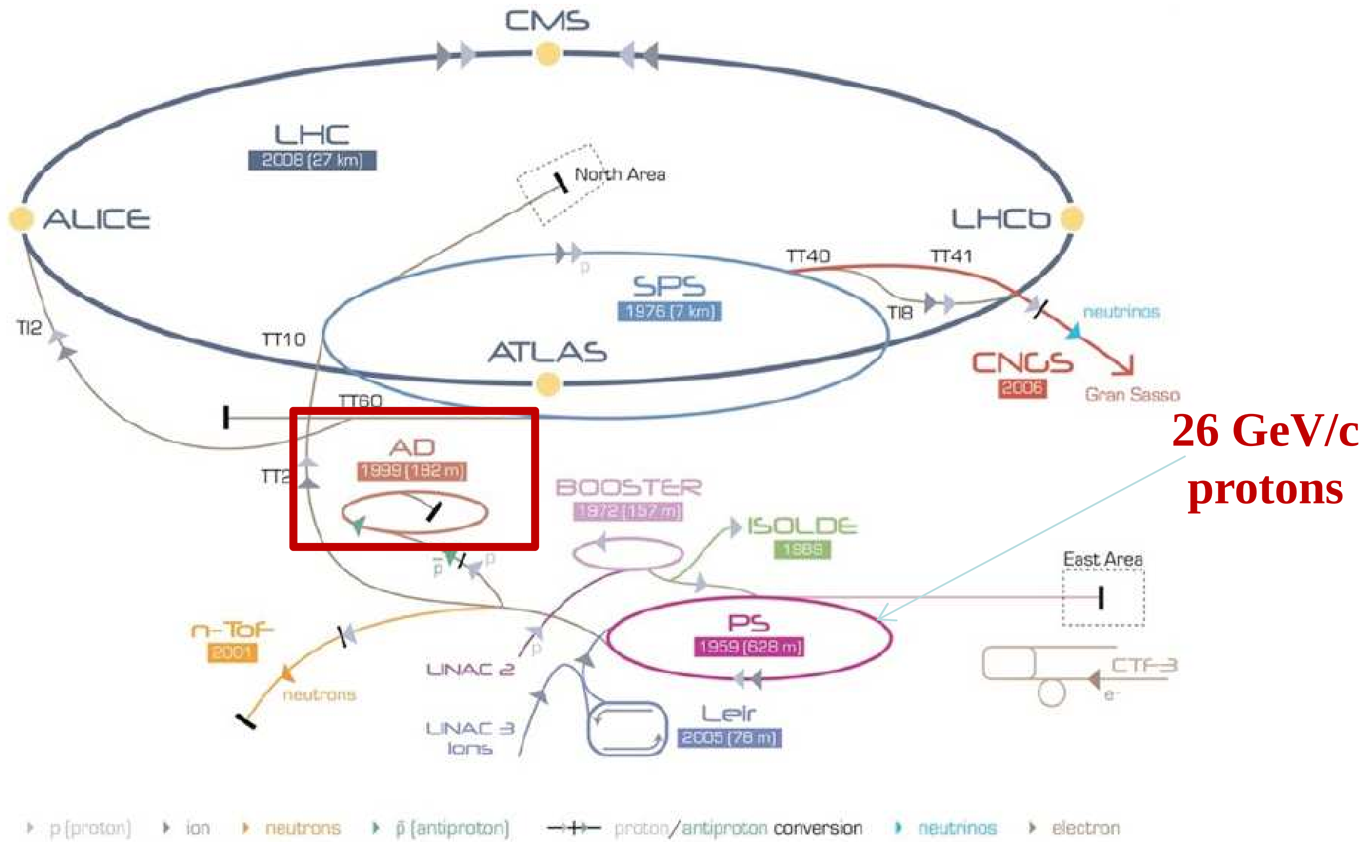


$g/2 = 2.792\ 847\ 350\ (7)\ (6)$

- **First direct high-precision measurement of the proton magnetic moment**
- **Accuracy of 3.3 ppb**
- **Improves 42 year old Maser measurement by factor of 2.5 (D. Kleppner, MIT)**
- **Value in agreement with accepted CODATA value**

A. Mooser *et al.*, Nature **509**, 596 (2014).
P. F. Winkler *et al.*, Phys. Rev. A **5**, 83 (1972).

CERN's Antiproton Decelerator (AD) near Geneva, Switzerland

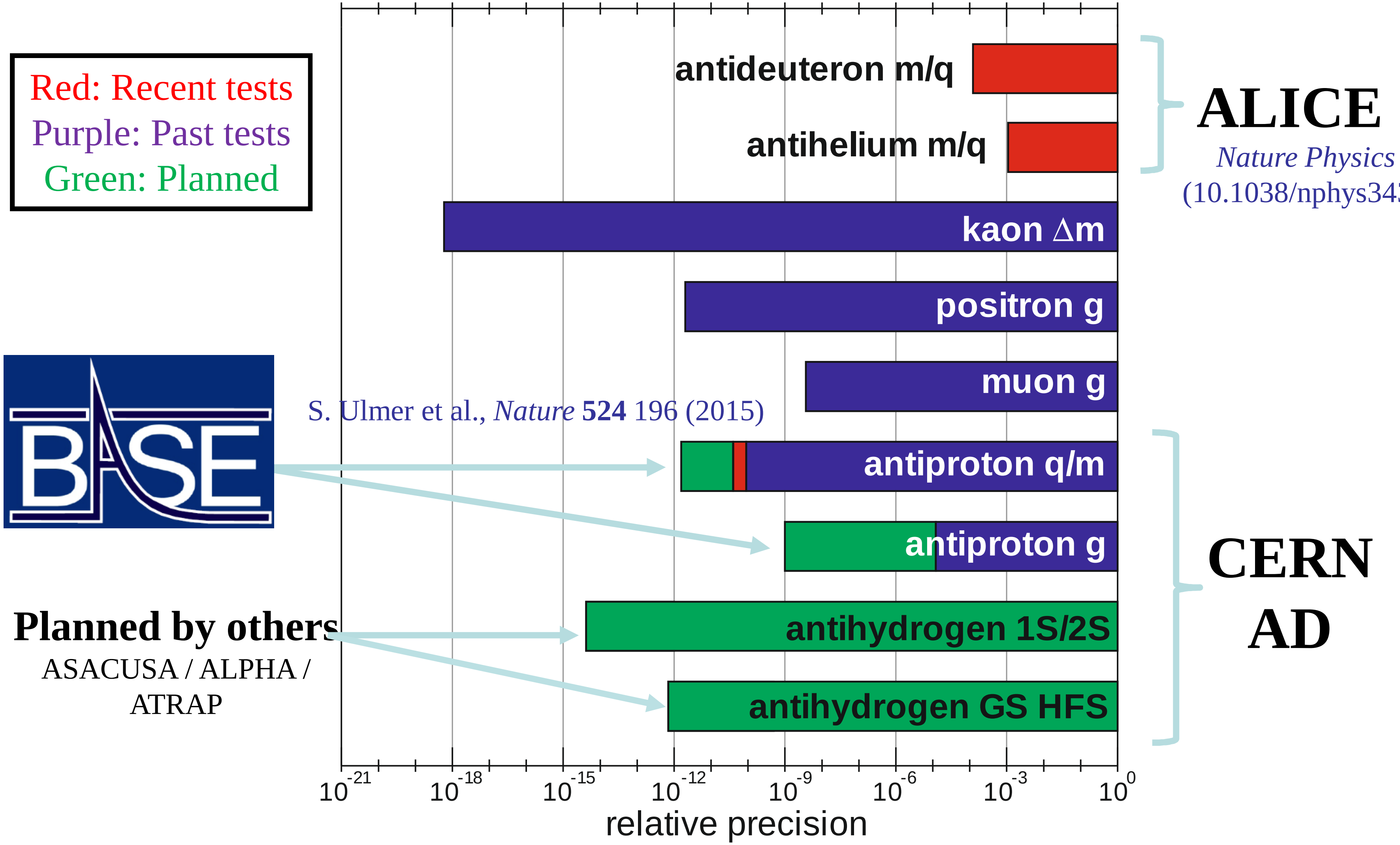


Overview: CPT-Tests

BASE: Baryon Antibaryon Symmetry Experiment

Spokesperson: Stefan Ulmer

Red: Recent tests
Purple: Past tests
Green: Planned

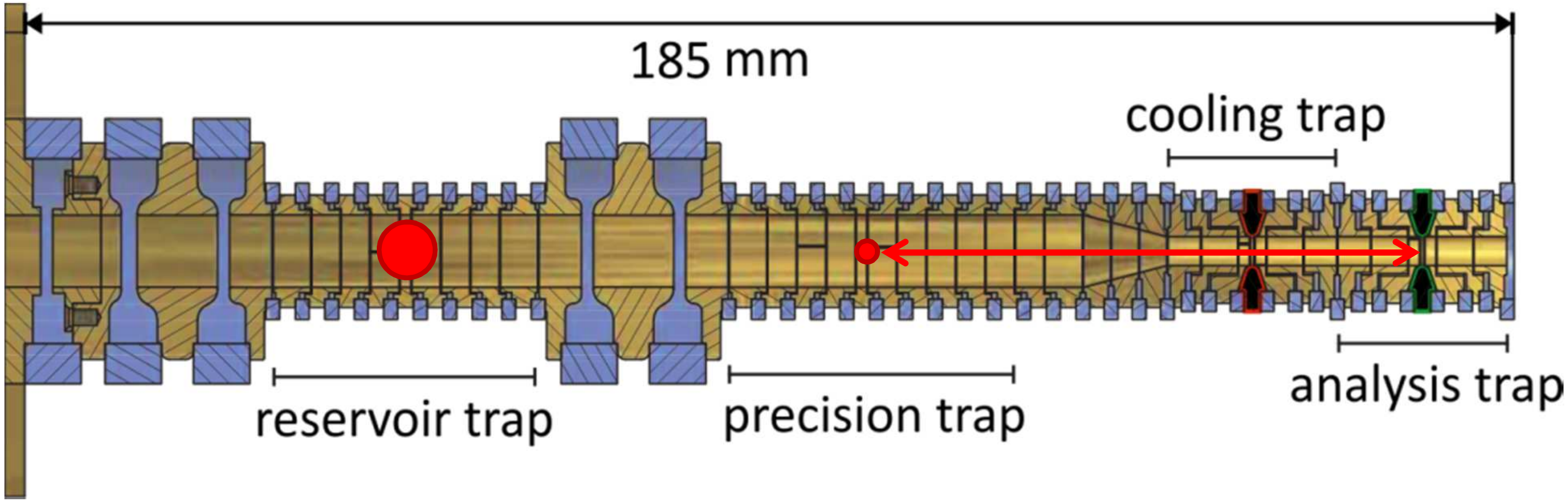


Nature Physics (10.1038/nphys3432)

S. Ulmer et al., *Nature* **524** 196 (2015)

Planned by others
ASACUSA / ALPHA / ATRAP

The four Penning-trap system of BASE / CERN, Geneva, Switzerland



- 4 months measurement time for antiproton g-factor
- Data collection time independent of accelerator run-times.

Long storage of an antiproton cloud from Nov. 2015
Non-destructive extraction from the reservoir

BASE Collaboration

Stefan Ulmer (Spokesperson), Kurt Franke (PhD), Takashi Higuchi (Master), Andreas Mooser (PD), Hiroki Nagahama (PhD), Georg Schneider (PhD), Simon Van Gorp (PD), Matthias Borchert (Bachelor), Andrej Gheorghe (Summer Student)

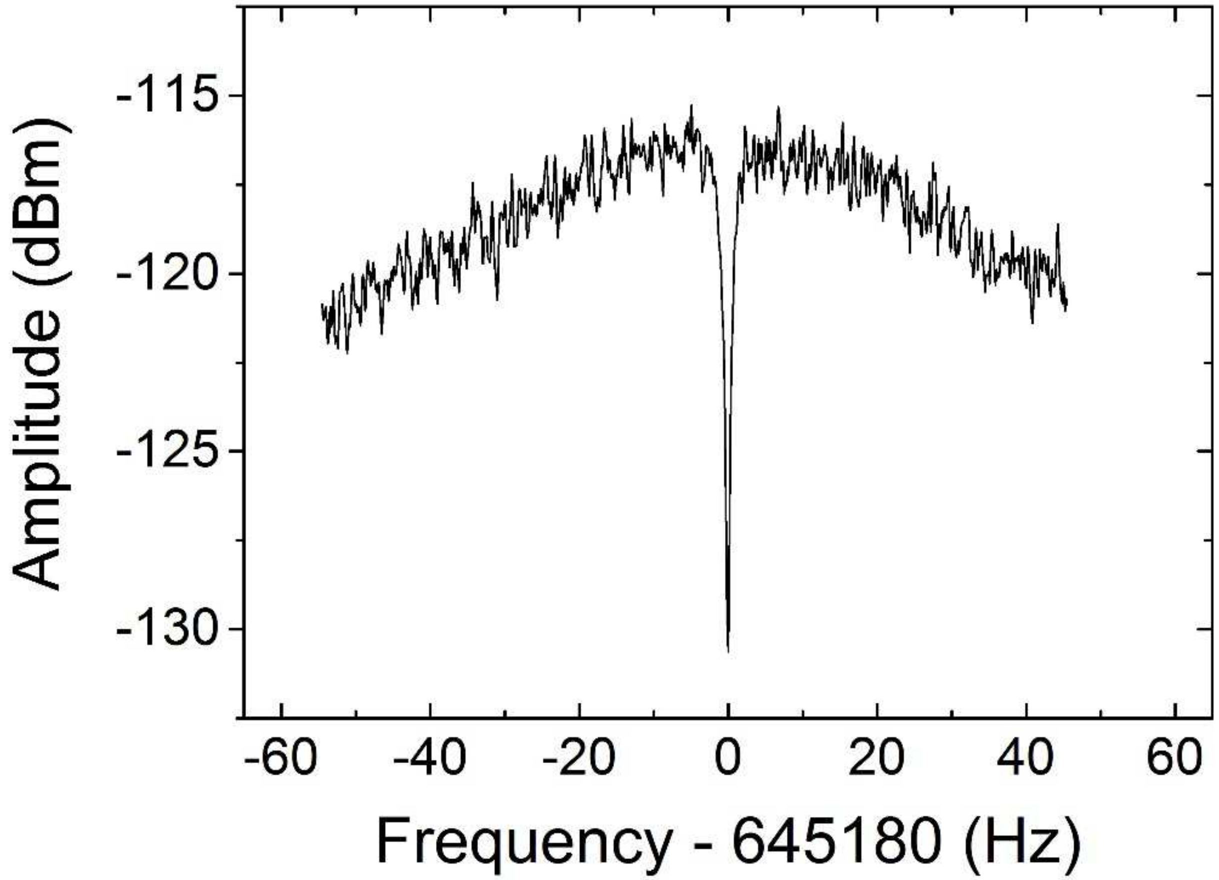
Senior Members:

Klaus Blaum, Yasuyuki Matsuda, Wolfgang Quint, Yasunori Yamazaki, Jochen Walz

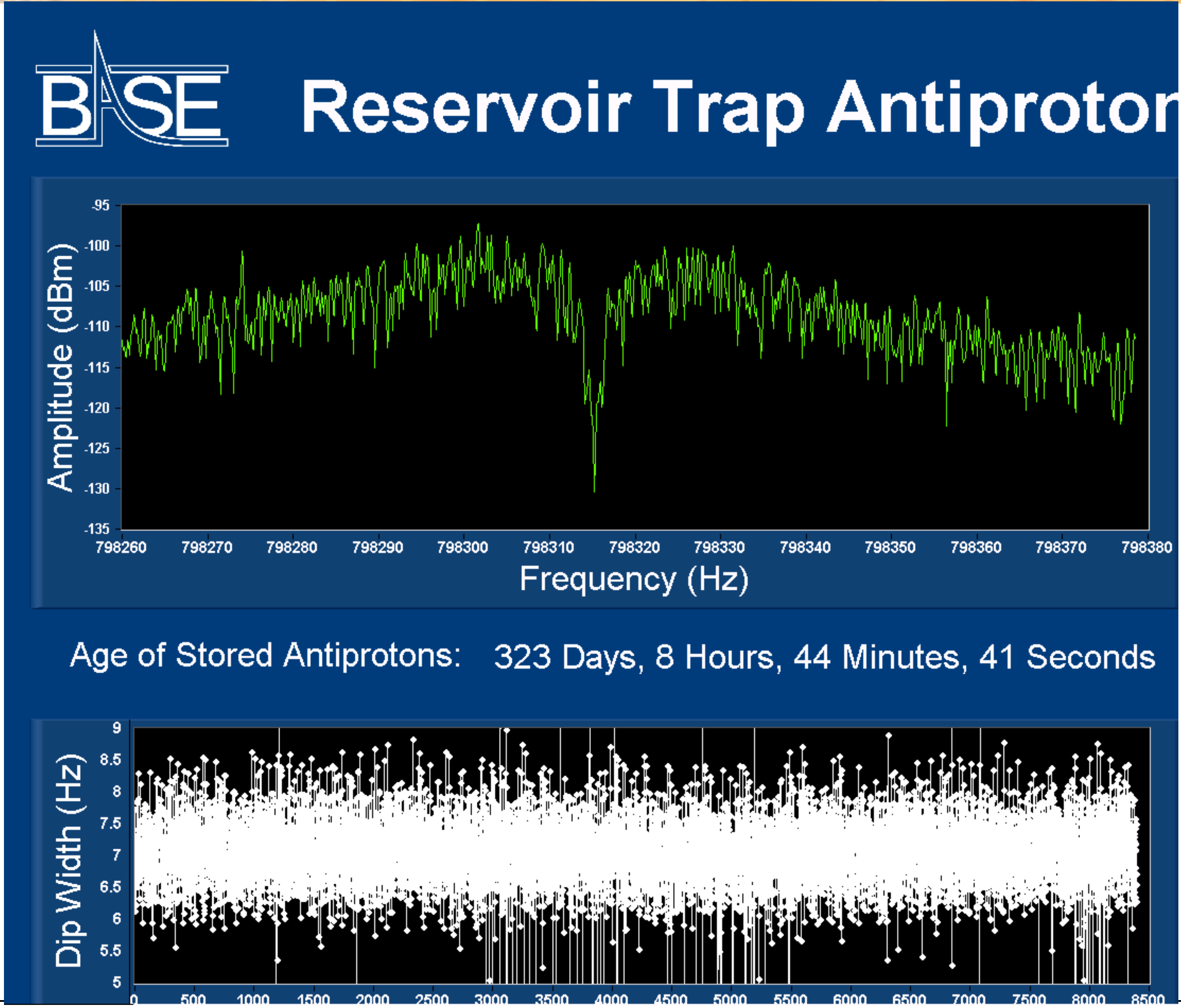
CERN/AD Staff: Lajos Botjar, Francois Butin, …

Our first single antiproton

- antiproton cooled to T = 4 K



Two trapped antiprotons today, 30 September 2016, at noon time - loaded on 12 November 2015



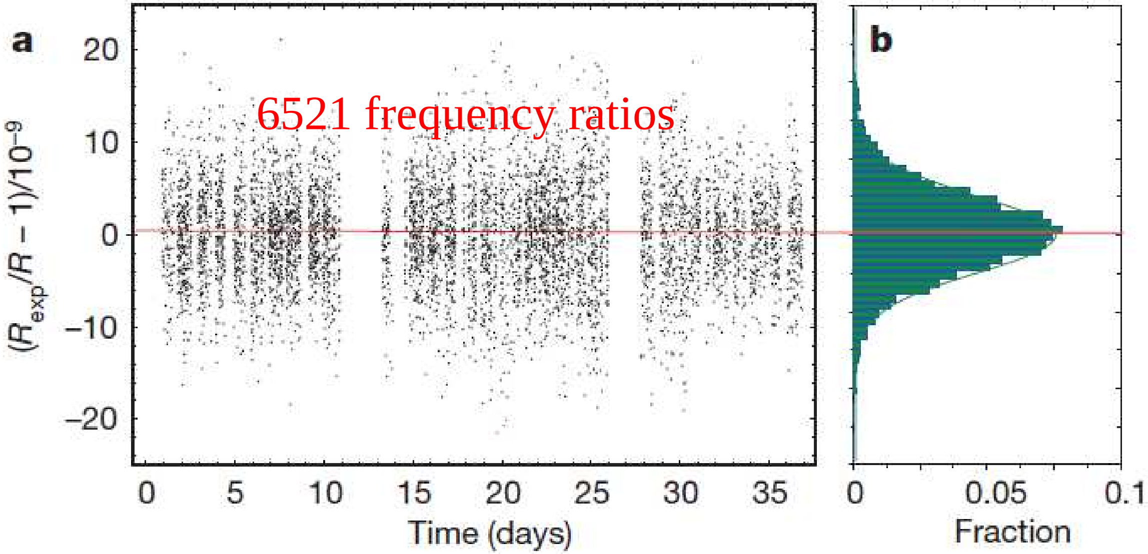
courtesy of:
Stefan Ulmer
Christian Smorra
Stefan Sellner
at CERN

LETTER

OPEN
doi:10.1038/nature14861

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

S. Ulmer[1], C. Smorra[1,2], A. Mooser[1], K. Franke[1,3], H. Nagahama[1,4], G. Schneider[1,5], T. Higuchi[1,4], S. Van Gorp[6], K. Blaum[3], Y. Matsuda[4], W. Quint[7], J. Walz[5,8] & Y. Yamazaki[6]

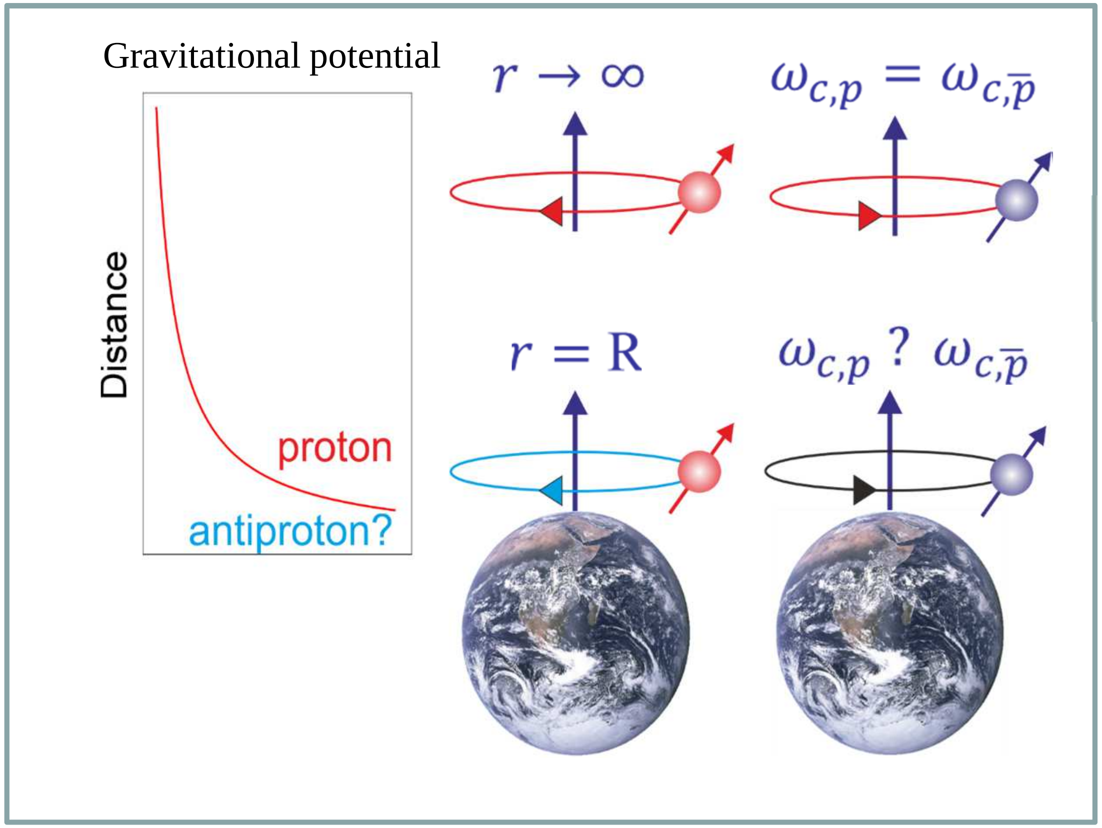


Final result

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

- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

Proton/antiproton gravitational redshifts



- Constraint of the gravitational anomaly for antiprotons:

$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\, U/c^2$$

Our 69 ppt result sets a new upper limit of

$$|\alpha_g - 1| < 8.7 \times 10^{-7}$$

Assuming CPT Invariance, we can compare the proton/antiproton gravitational redshift.

R. J. Hughes, & M. H. Holzscheiter, Phys. Rev. Lett. 66, 854-857 (1991).
R. J. Hughes, Contemporary Physics, 34:4, 177-191 (1993).

Acknowledgements

Helmholtz-Institut Jena
Friedrich-Schiller-Universität Jena

seit 1558

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

GSI

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Deutsche Forschungsgemeinschaft DFG

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

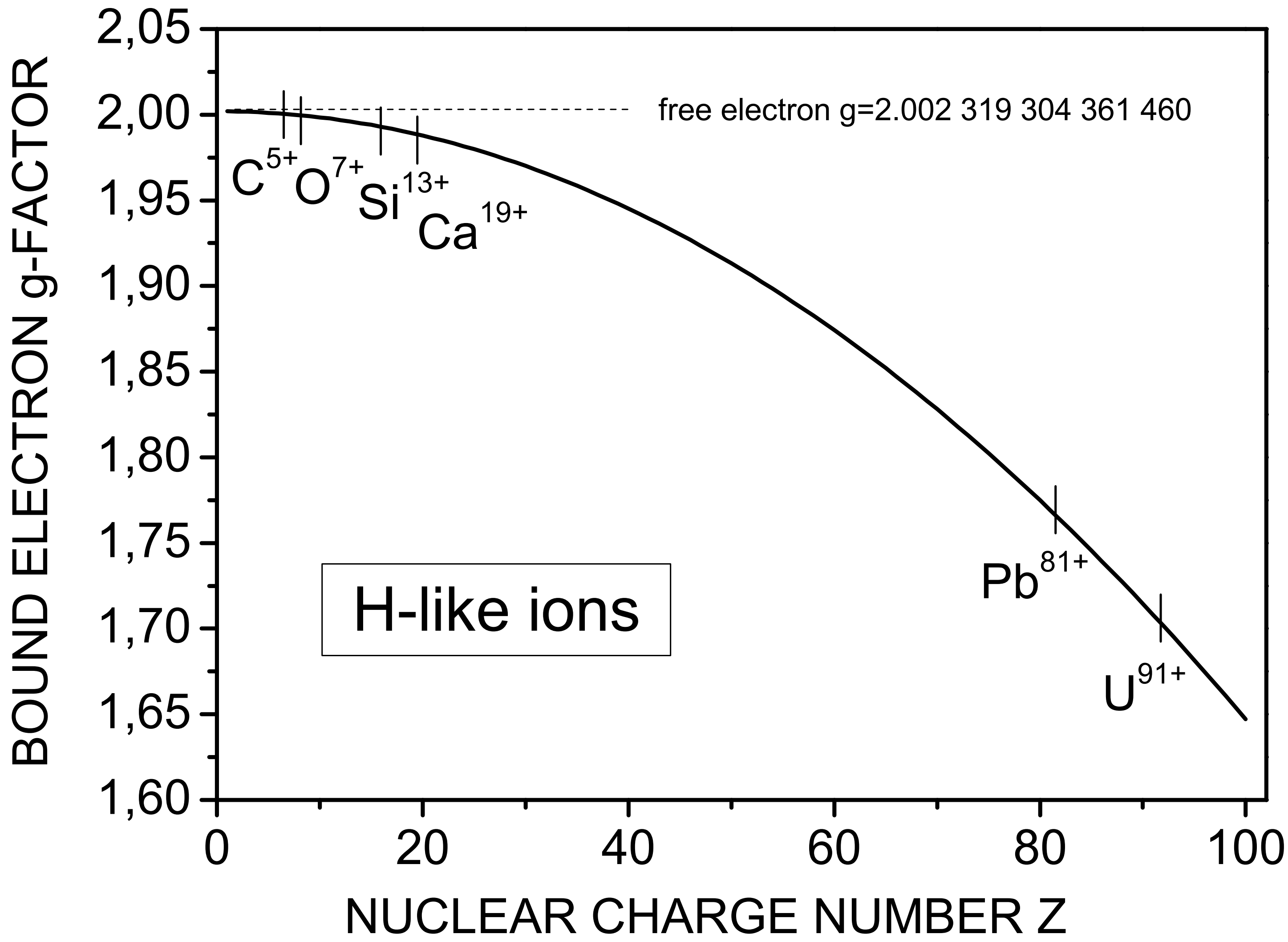
RIKEN

CERN

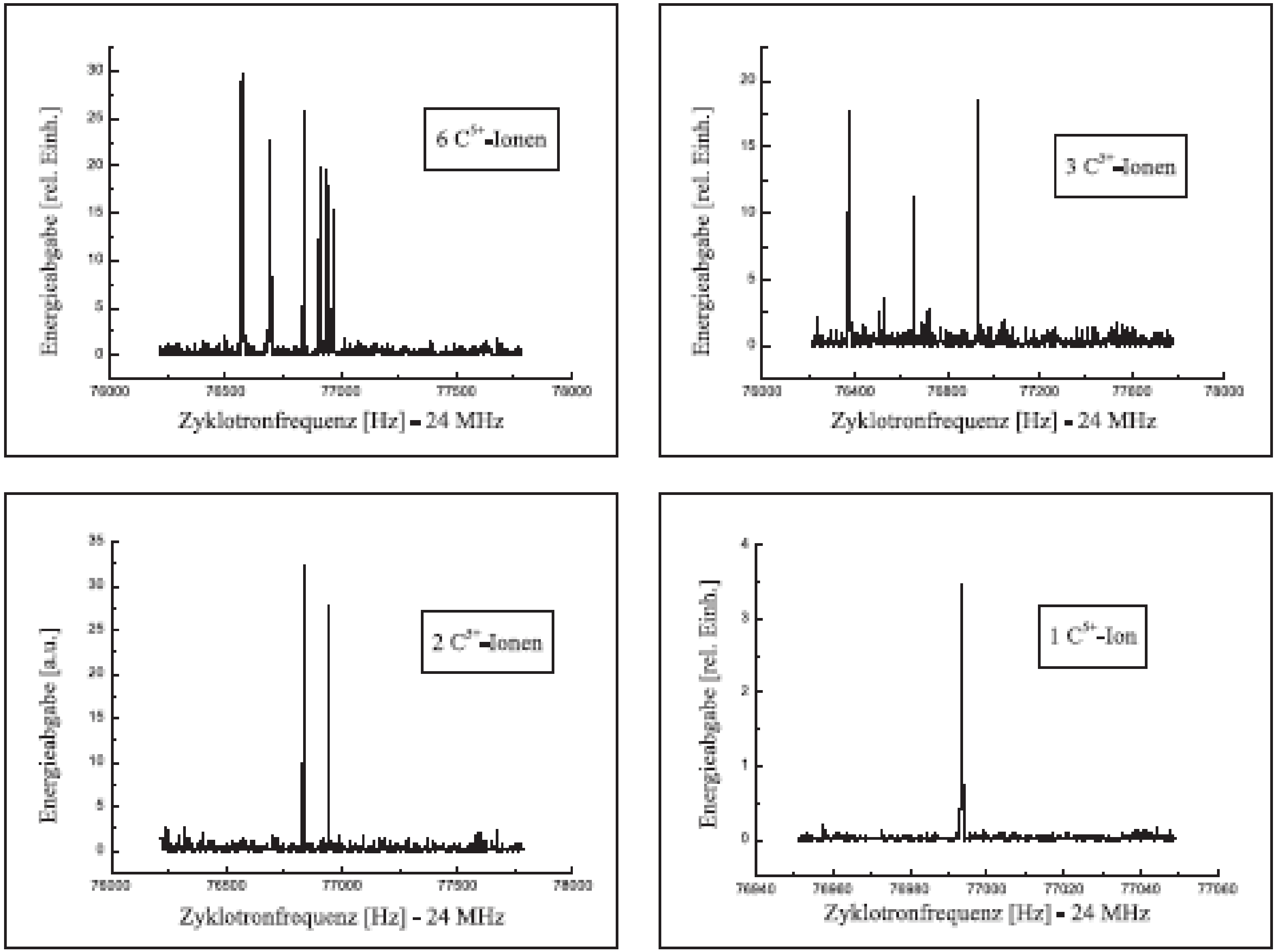
Thank you for your attention !


Center for Quantum Dynamics
EMMI
Conference on Precision Physics, Quantum Electrodynamics and Fundamental Interactions
April 30th to May 5th 2017
IESC Cargèse, Corsica, France
Main topics: Precision experiments
Bound-state QED in atoms, molecules, ions
Physics of highly charged ions
Fundamental constants
The proton size puzzle
Matter/antimatter symmetry tests
Organizers: Laurent Hilico (LKB and Evry University)
Jean-Philippe Karr (LKB and Evry University)
Wolfgang Quint (GSI Darmstadt and HI Jena)
Manuel Vogel (GSI Darmstadt and HI Jena)
http://indico.gsi.de/event/cargese2017

Bound-electron g-factor in hydrogen-like ions



Isolating a single highly charged ion



Available online at www.sciencedirect.com

ScienceDirect

PHYSICS LETTERS B

Physics Letters B 661 (2008) 287–289

www.elsevier.com/locate/physletb

A new test for dark matter particles of low mass

Céline Bœhm [a,*], Joseph Silk [b]

[a] *LAPTH, UMR 5108, 9 chemin de Bellevue, BP 110, 74941 Annecy-Le-Vieux, France*
[b] *Astrophysics Department, DWB Keble road, OX1 3RH Oxford, UK*

Received 11 February 2008; accepted 11 February 2008

Available online 14 February 2008

Concept of CPT violation

$$H' = H_{SM} + \Delta V \quad \Rightarrow \quad < \psi^* | \Delta V | \psi > = \Delta E$$

System based on SM

CPT violating term

different C's

$$\mathcal{L}_p = \frac{\lambda}{M} \langle T \rangle \bar{\psi} \Gamma (i\partial)^k \psi$$

Kostelecky et al.

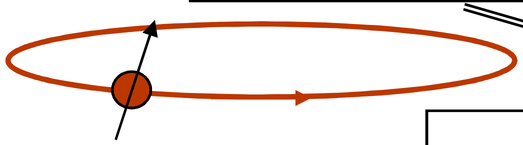
- Absolute energy resolution (normalized to m-scale) might be a more appropriate measure to characterize the sensitivity of an experiment with respect to CPT violation.
- Single particle measurements in Penning traps give high energy resolution.

	Relative precision	Energy resolution	SME Figure of merit
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	$\sim 10^{-18}$
p-p̄ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	$\sim 10^{-26}$
p-p̄ *g*-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	$\sim 10^{-21}$

Continuous Stern-Gerlach effect

spin has magnetic moment μ

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



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

↓

attractive or repulsive force $F_{magn}(z) = \pm 2\mu B_2 z$

↓

axial frequency = f (spin direction)