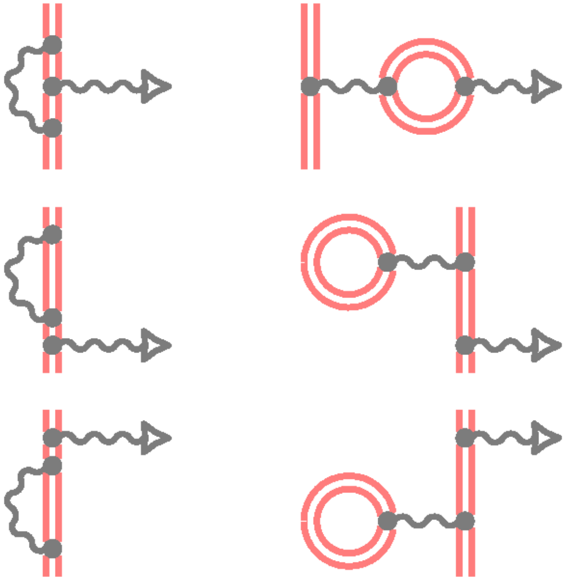
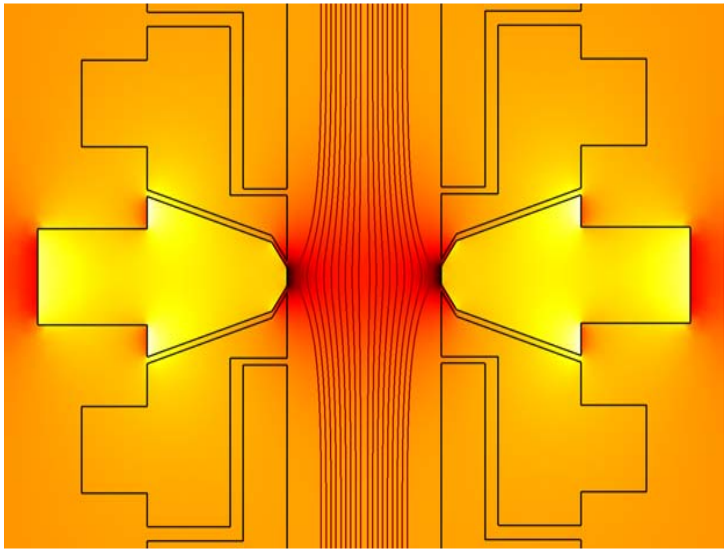
Atomic Physics in Traps

QED – Fundamental Constants – CPT Invariance



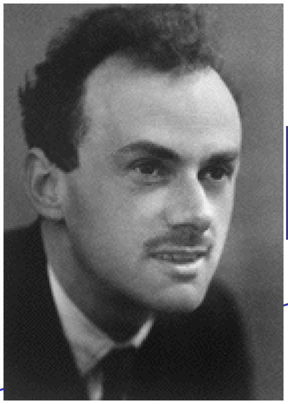


Wolfgang Quint
GSI Darmstadt and Univ. Heidelberg

Quantum mechanics, Relativity, and P.A.M. Dirac

Quantum mechanics

Special Relativity



Dirac theory

electron magnetic moment

energy levels of H-like ions

negative energy states

existence of anti-matter

g-factor

Lamb shift

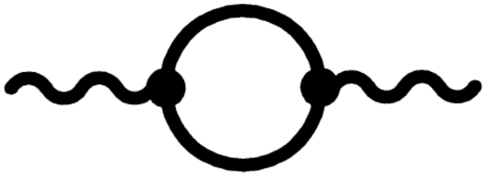
few-el. ions

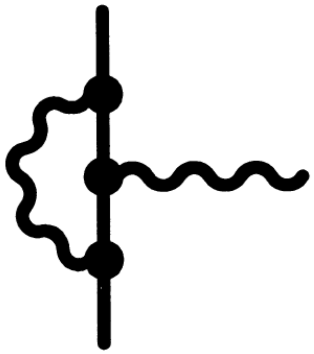
CPT tests

Quantum Electrodynamics (QED)

QED = Dirac theory + quantized radiation field

basic processes in QED:





self energy **vacuum polarization** **vertex correction**

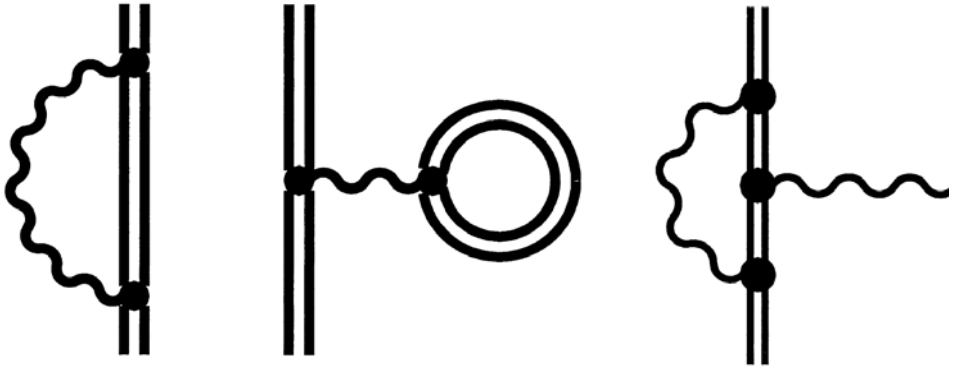
QED coupling parameter: finestructure constant $\alpha = e^2/2\varepsilon_0 hc \approx 1/137 \approx 0.007$

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

QED and highly charged ions

bound-state QED: quantum physics in strong fields

basic processes in bound-state QED:

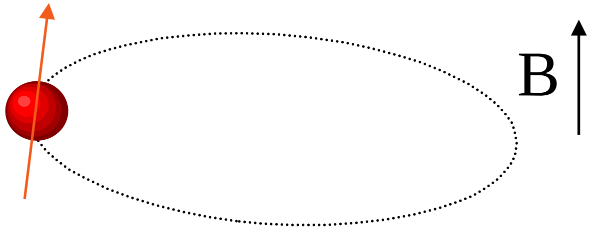


self energy   vacuum polarization vertex correction

bound-state QED coupling parameter for U^{91+}: $Z\alpha \approx 0.67$

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

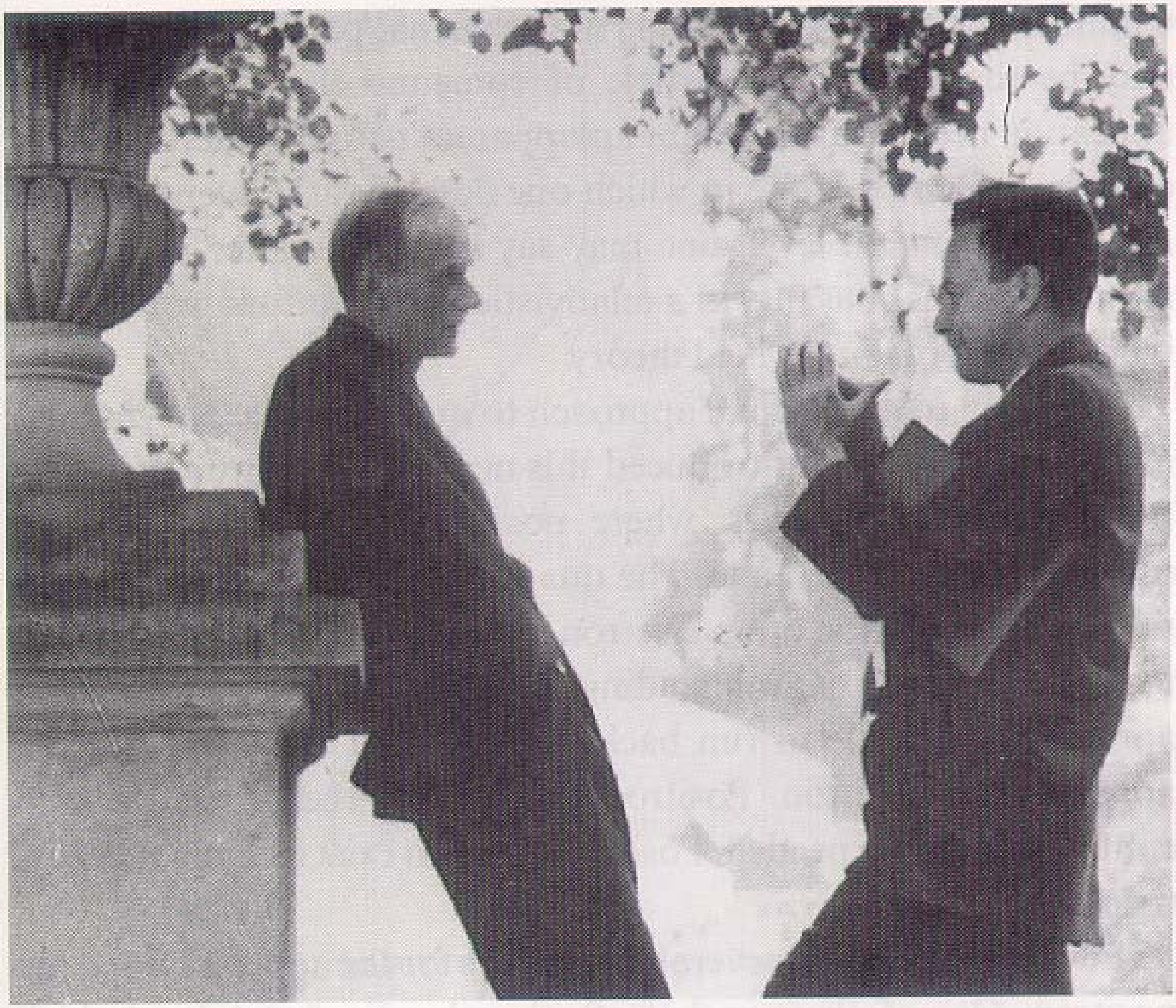
Magnetic moment (g-factor) of the electron



$$\mu = g \cdot \frac{e}{2m} J$$

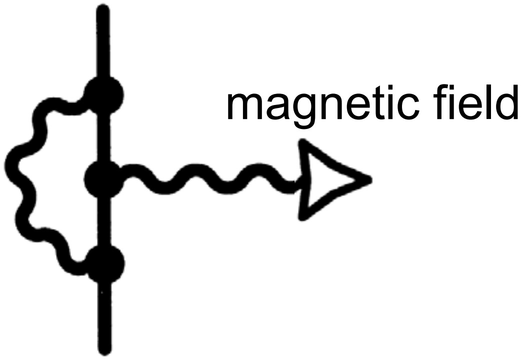
m: magnetic moment
g: g-factor
e: charge
m: mass
J: angular momentum

$g = 2 + \alpha / \pi$

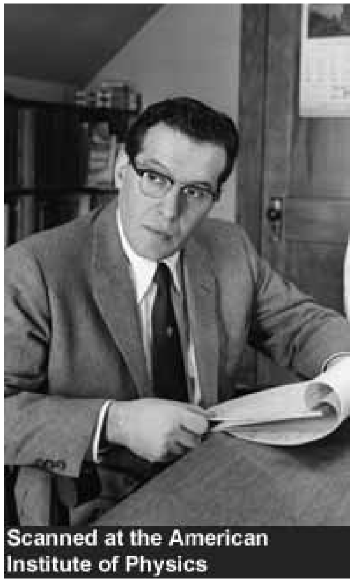


QED contributions to the g-factor of the free electron

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



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

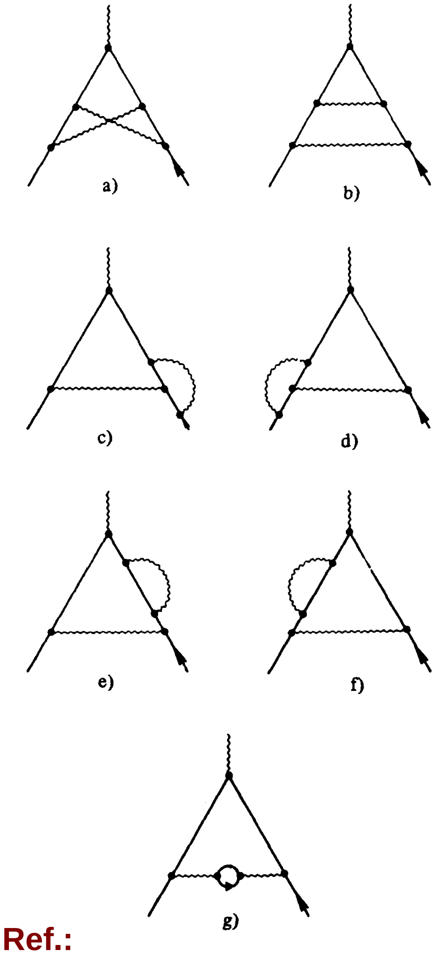


> The theory of quantum electrodynamics is,
> I would say, the jewel of physics
> - our proudest possession.
>
> *R. Feynman*

Ref.:
J. Schwinger, Phys. Rev. 73, 416 (1948); Hanneke et al., PRL 100, 120801 (2008)

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

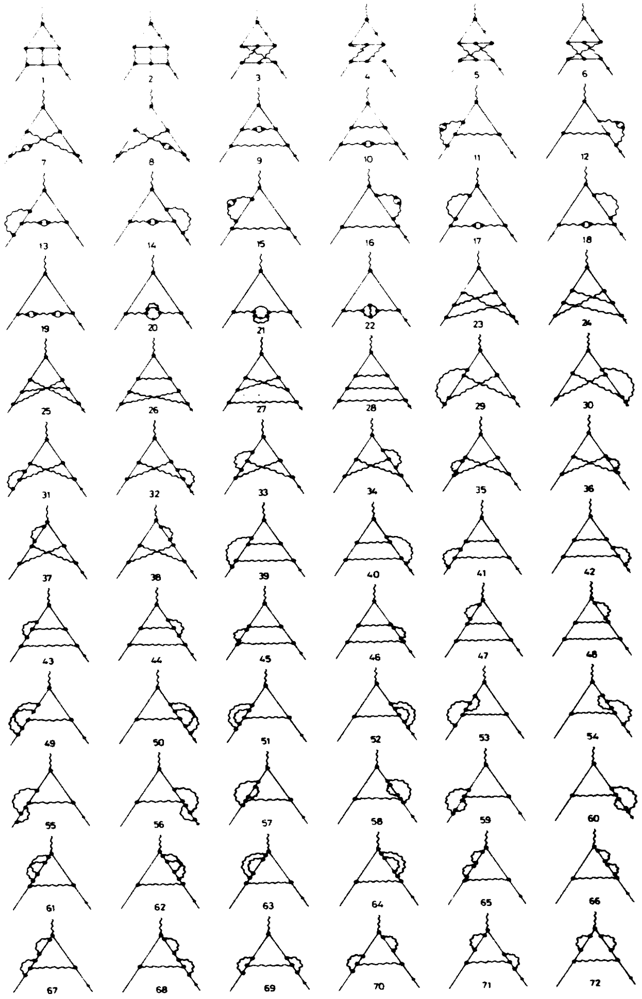
$$g_{free} = 2\,(1 + C_1\alpha/\pi + C_2(\alpha\,/\pi)^2 + C_3(\alpha\,/\pi)^3 + C_4(\alpha\,/\pi)^4 + C_5(\alpha\,/\pi)^5 + ...$$



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.:

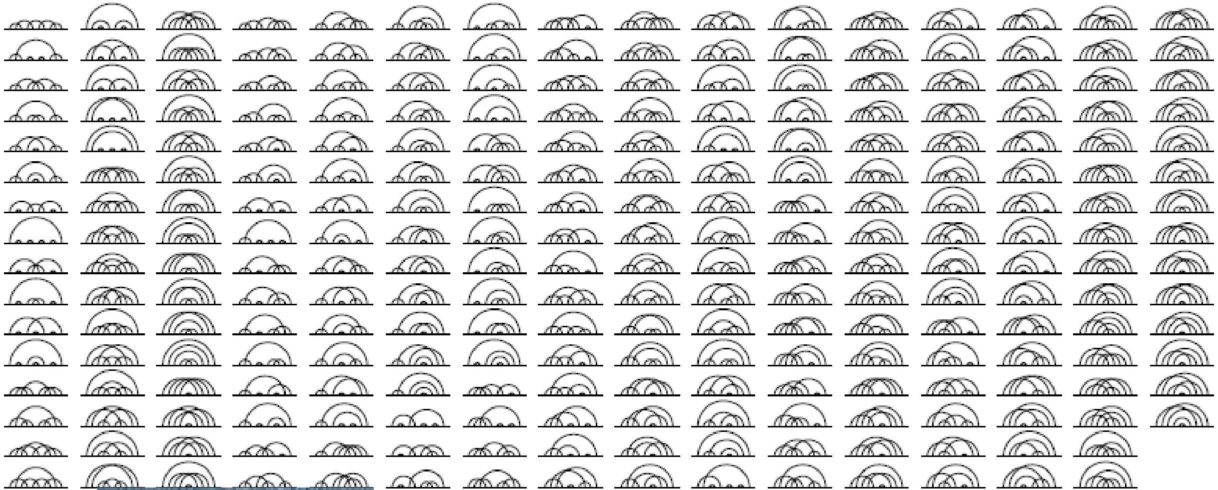
B. Lautrup et al., Phys. Rep. 3, 193 (1972)

Free electron: QED contributions of 5th order

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

Harvard g-2 measurement 2008:

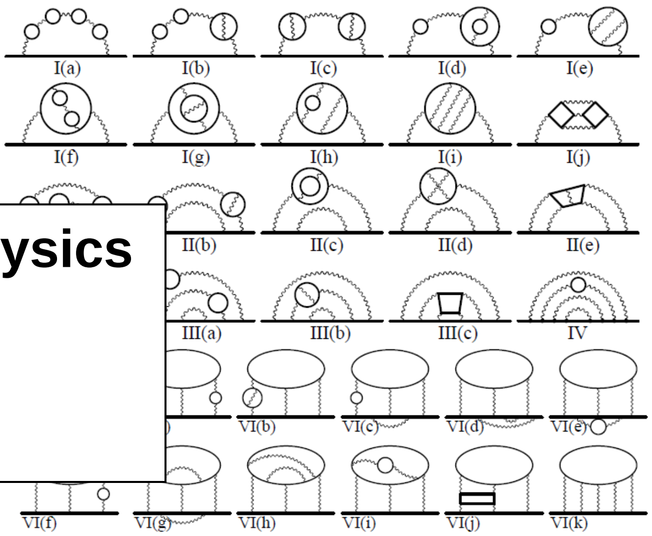
g_{free} = 2 (1.001 159 652 180 73 (28)) → determination of α



5th order in α:

$C_5 = 9.16$

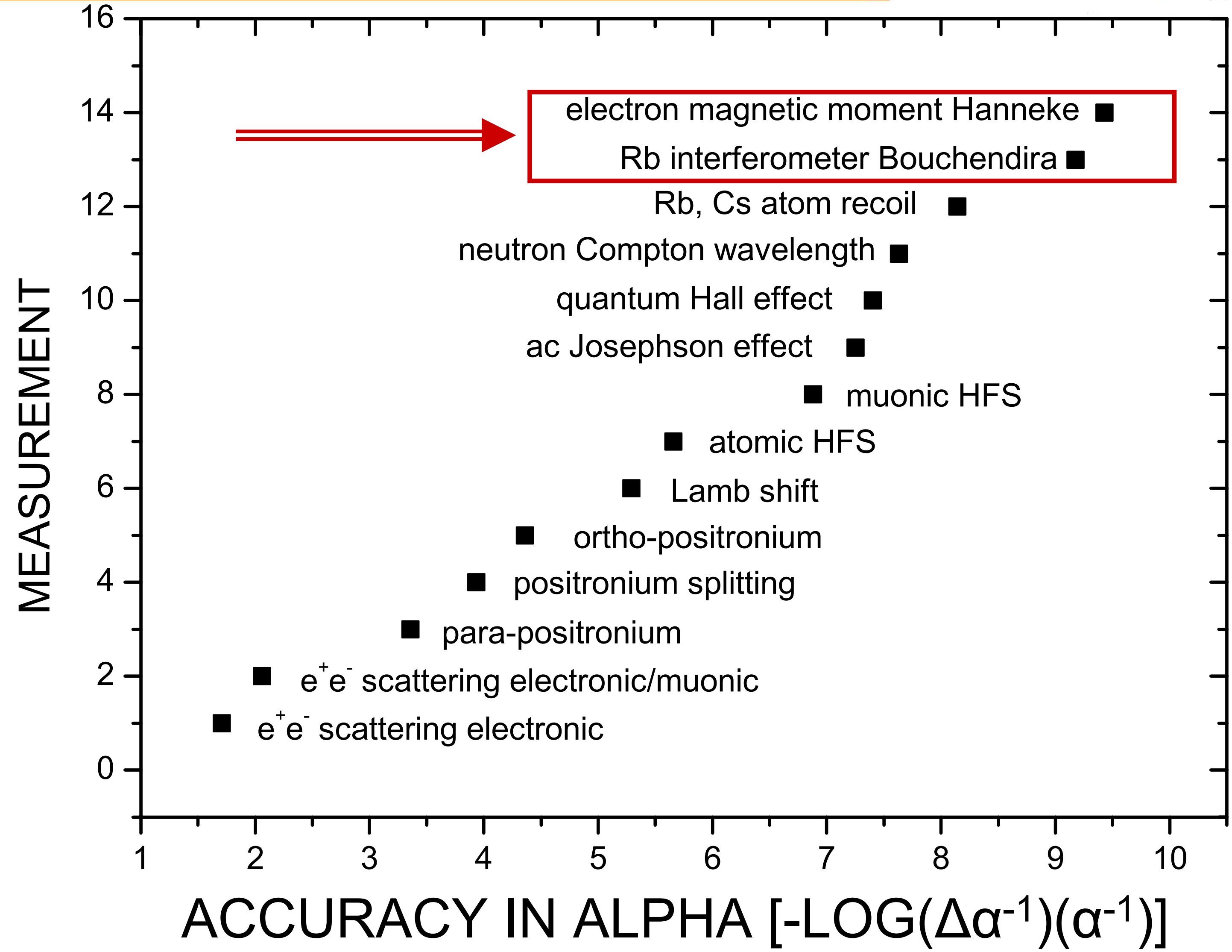
12672 graphs



> **„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

Determinations of the finestructure constant α



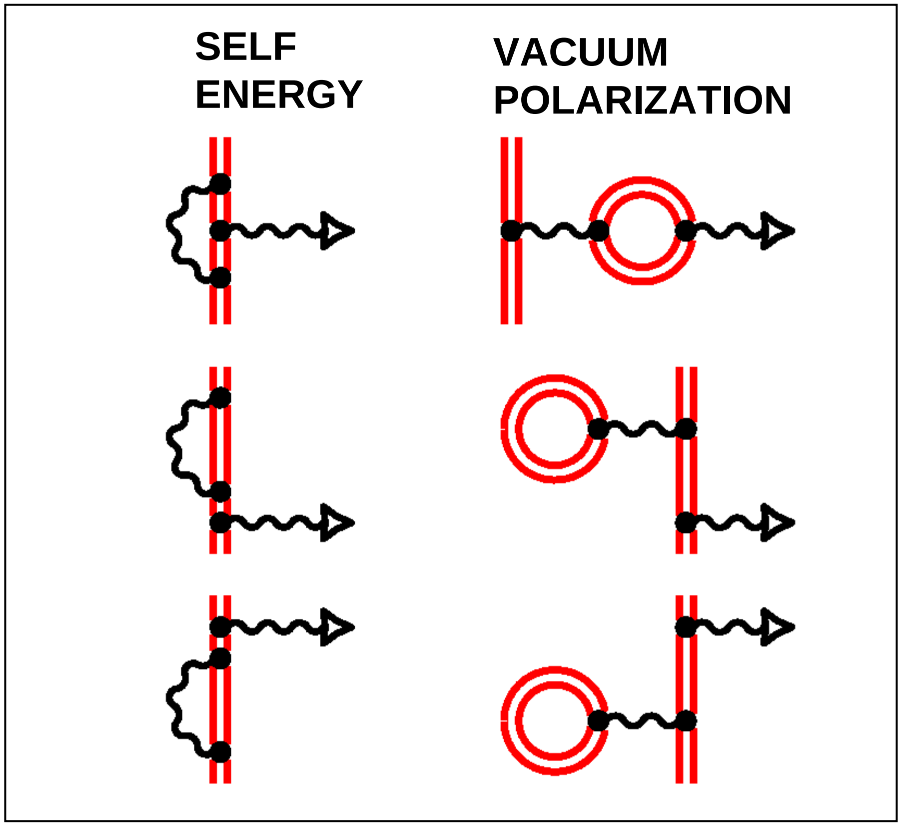
Ref.:
M. Vogel

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

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

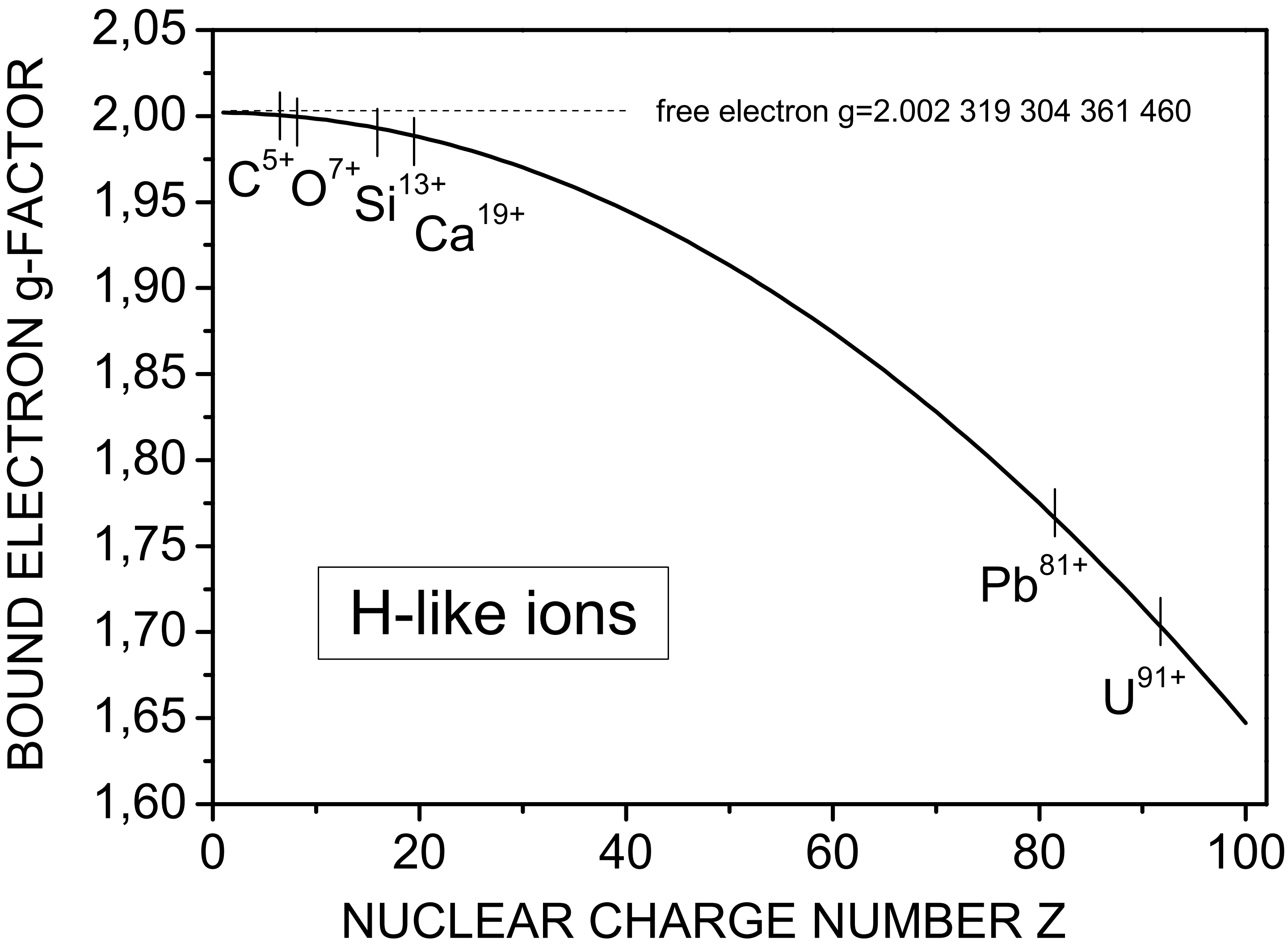
Dirac theory

bound-state QED



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

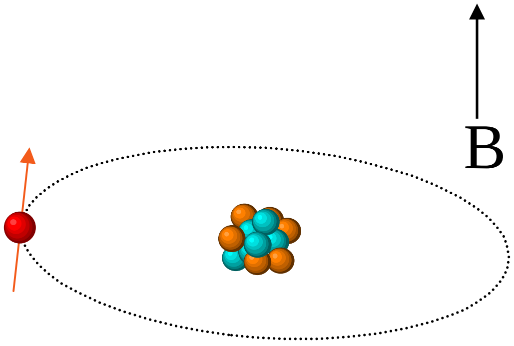
Bound-electron g-factor



g-Factor of the electron bound in a hydrogen-like ion

Larmor precession frequency of the bound electron:

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



Ion cyclotron frequency:

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

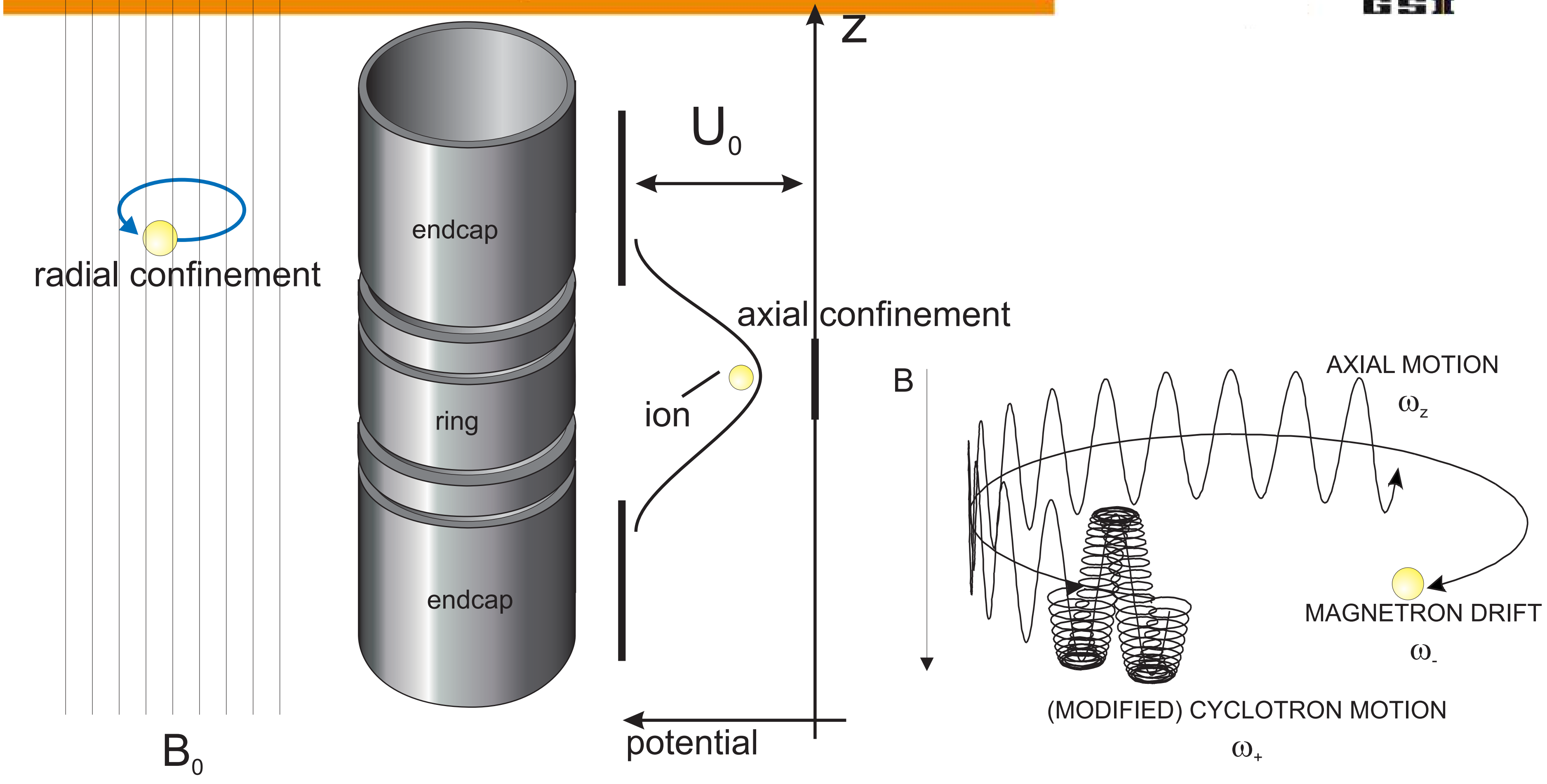
$$g_J = 2\cdot\frac{\omega_L^{e}}{\omega_c^{ion}}\cdot\frac{m_e}{M_{ion}}\cdot\frac{Q^{ion}}{e}$$

→ 'experimental g-factor'
→ comparison with theory

our measurement

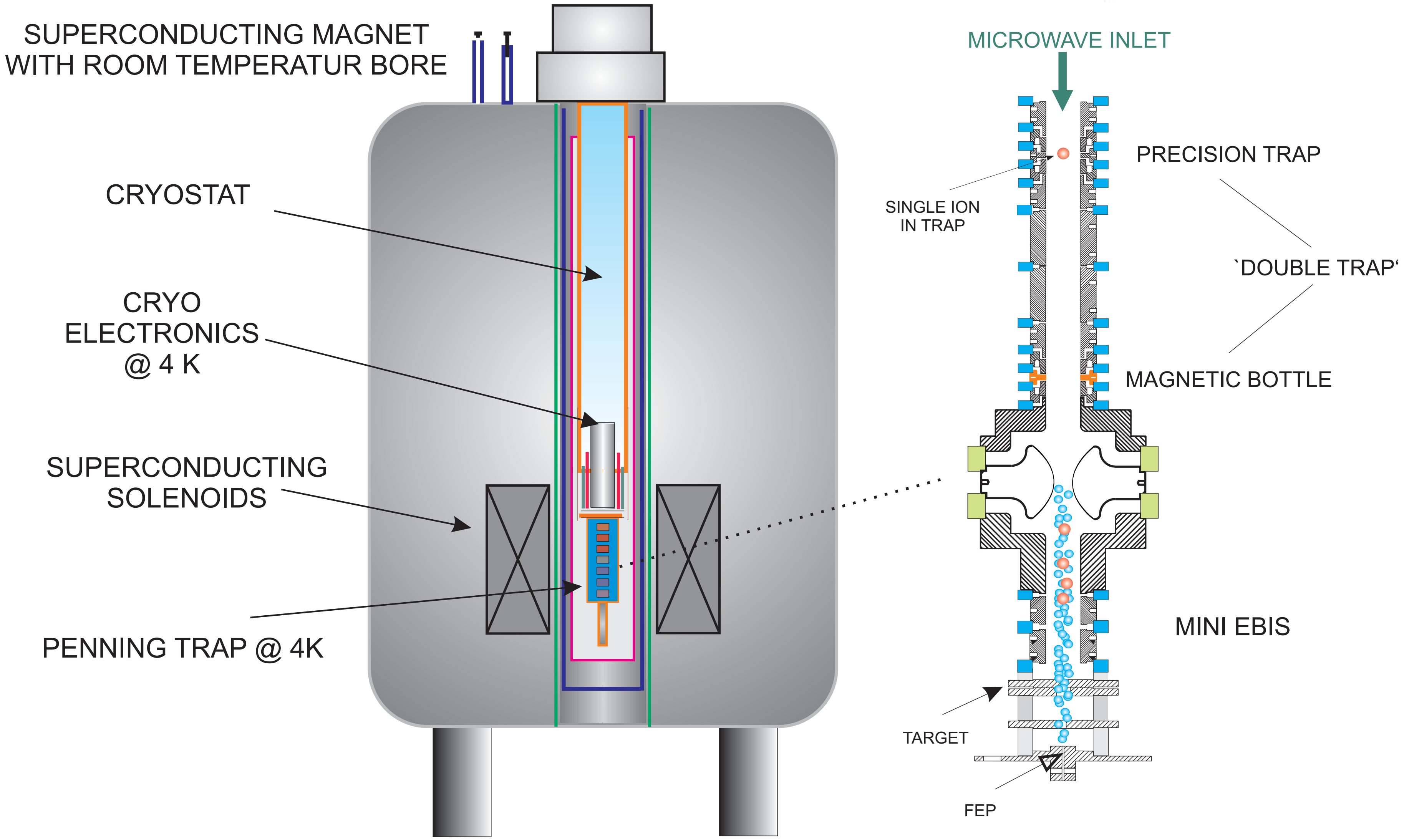
external input parameter

A single highly charged ion stored in a Penning trap



magnetic physical electric combined ion motion

Highly charged ion g-factor apparatus



SUPERCONDUCTING MAGNET
WITH ROOM TEMPERATUR BORE

CRYOSTAT

CRYO
ELECTRONICS
@ 4 K

SUPERCONDUCTING
SOLENOIDS

PENNING TRAP @ 4K

MICROWAVE INLET

PRECISION TRAP

SINGLE ION
IN TRAP

`DOUBLE TRAP‘

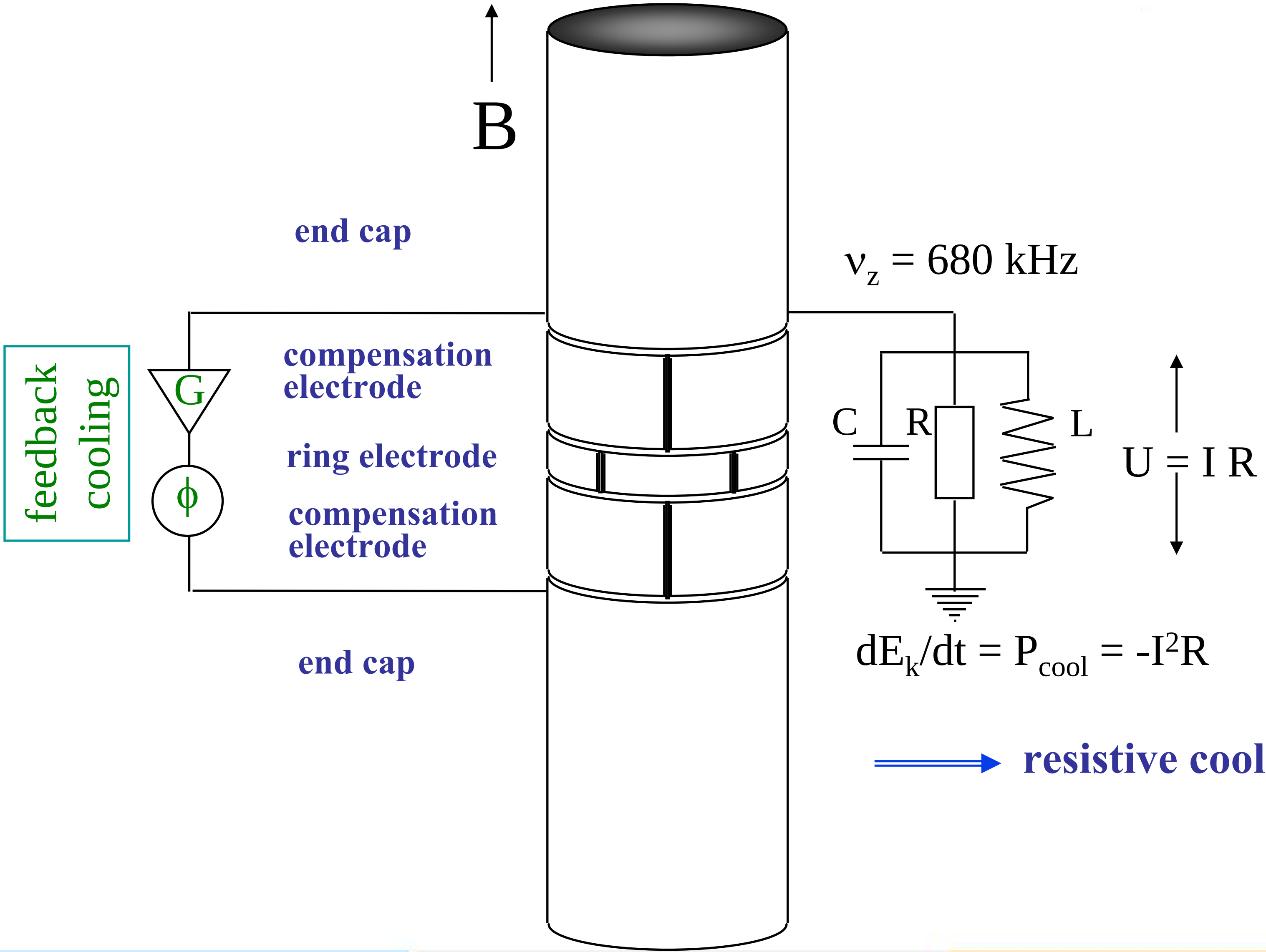
MAGNETIC BOTTLE

MINI EBIS

TARGET

FEP

Electronic detection of a single trapped ion: Resistive cooling and active feedback cooling



ν_z = 680 kHz

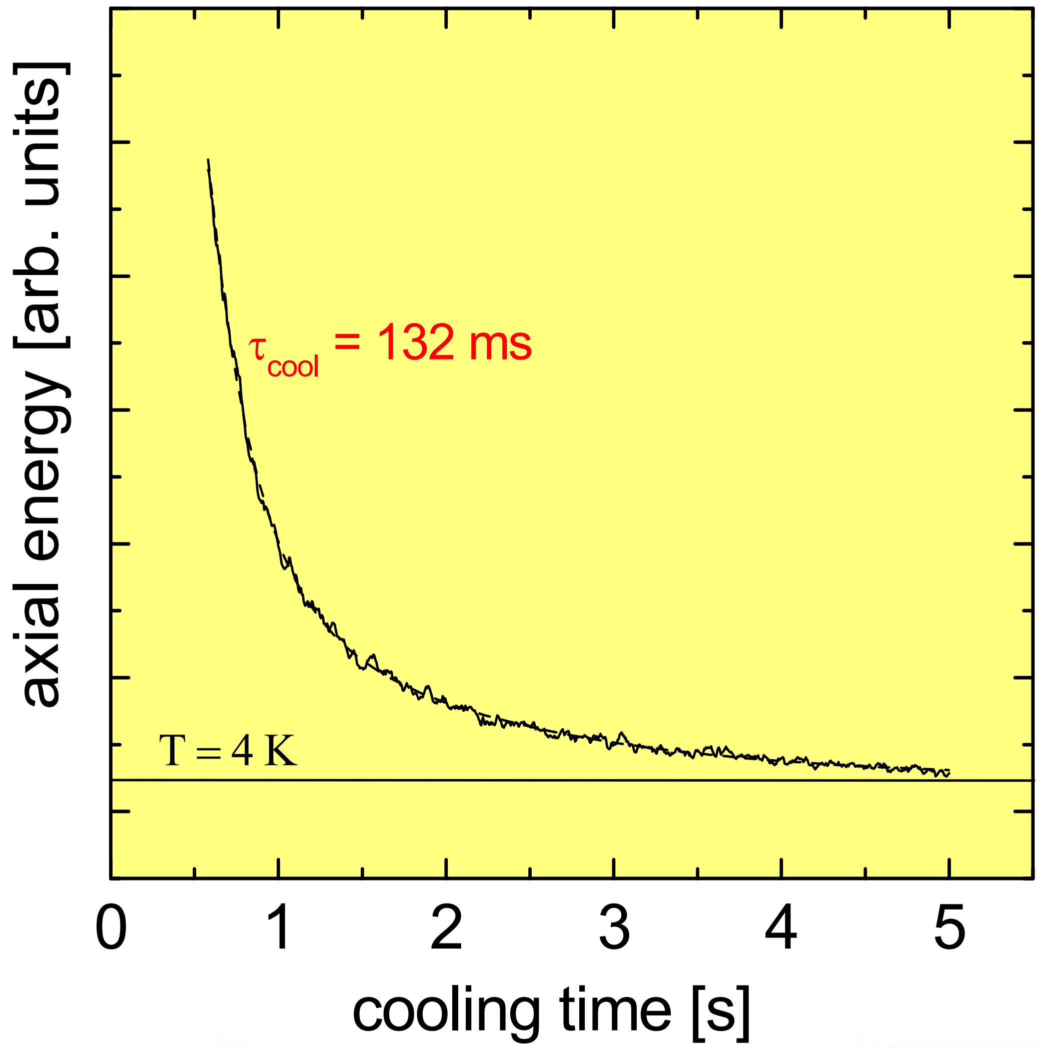
U = I R

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

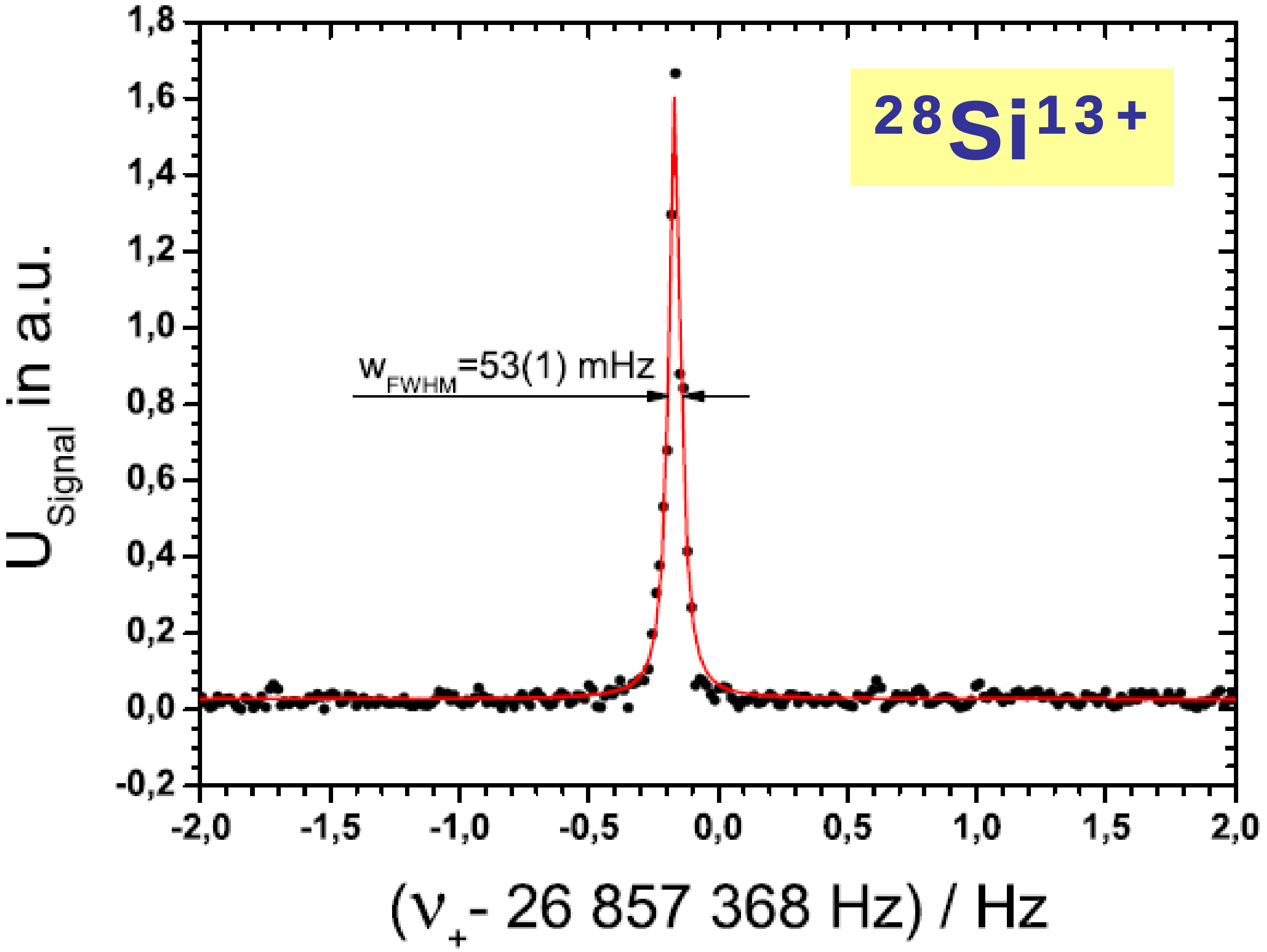
→ **resistive cooling**

Resistive cooling of trapped $^{12}C^{5+}$ ions

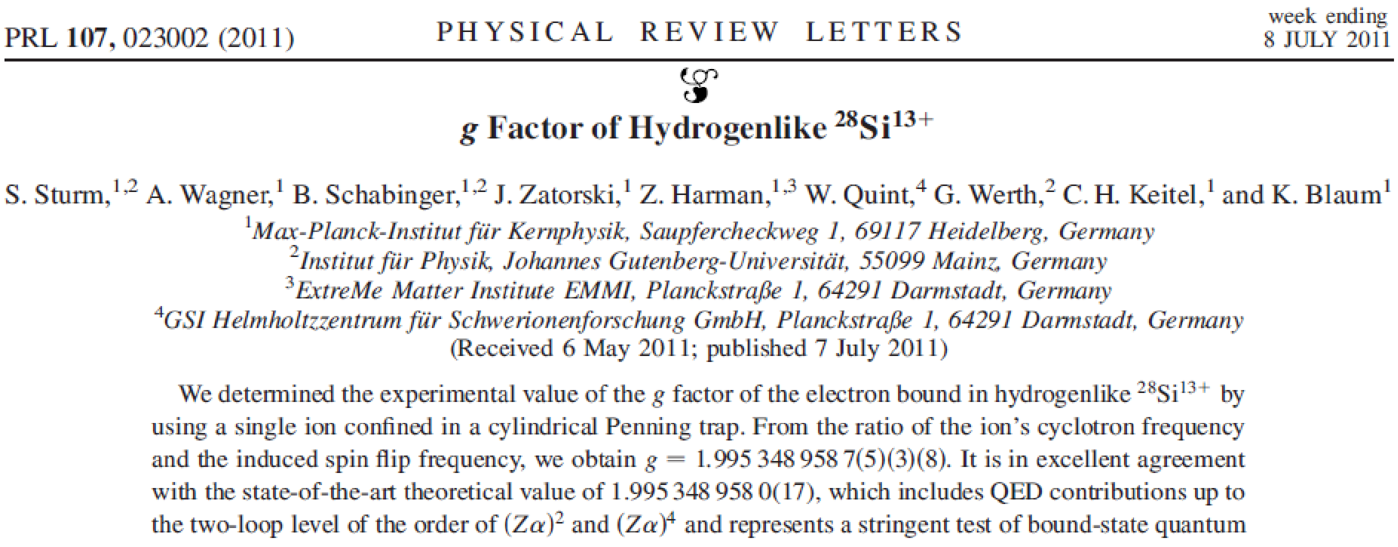
- final temperature: T = 4 Kelvin



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



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



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

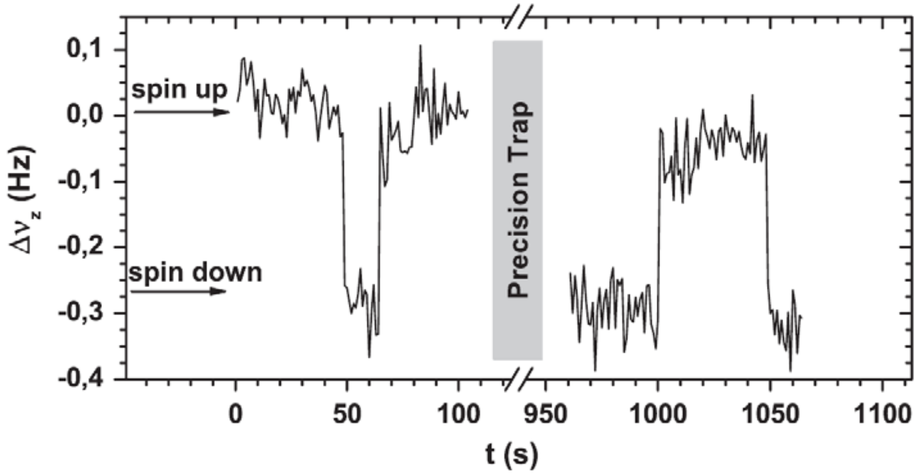
g Factor of Hydrogenlike $^{28}Si^{13+}$

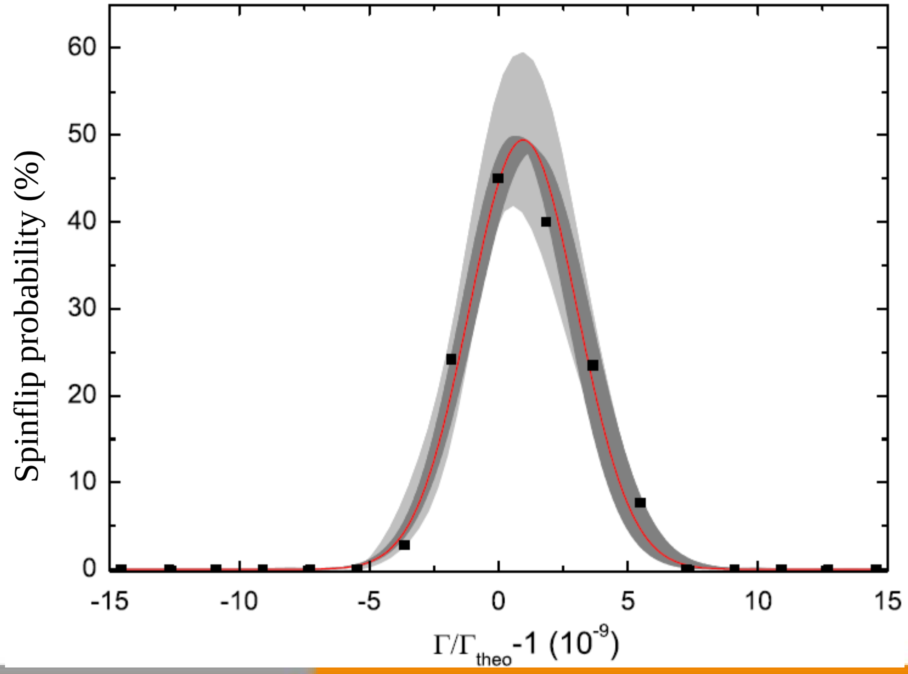
S. Sturm,[1,2] A. Wagner,[1] B. Schabinger,[1,2] J. Zatorski,[1] Z. Harman,[1,3] W. Quint,[4] G. Werth,[2] C. H. Keitel,[1] and K. Blaum[1]

[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 $^{28}Si^{13+}$

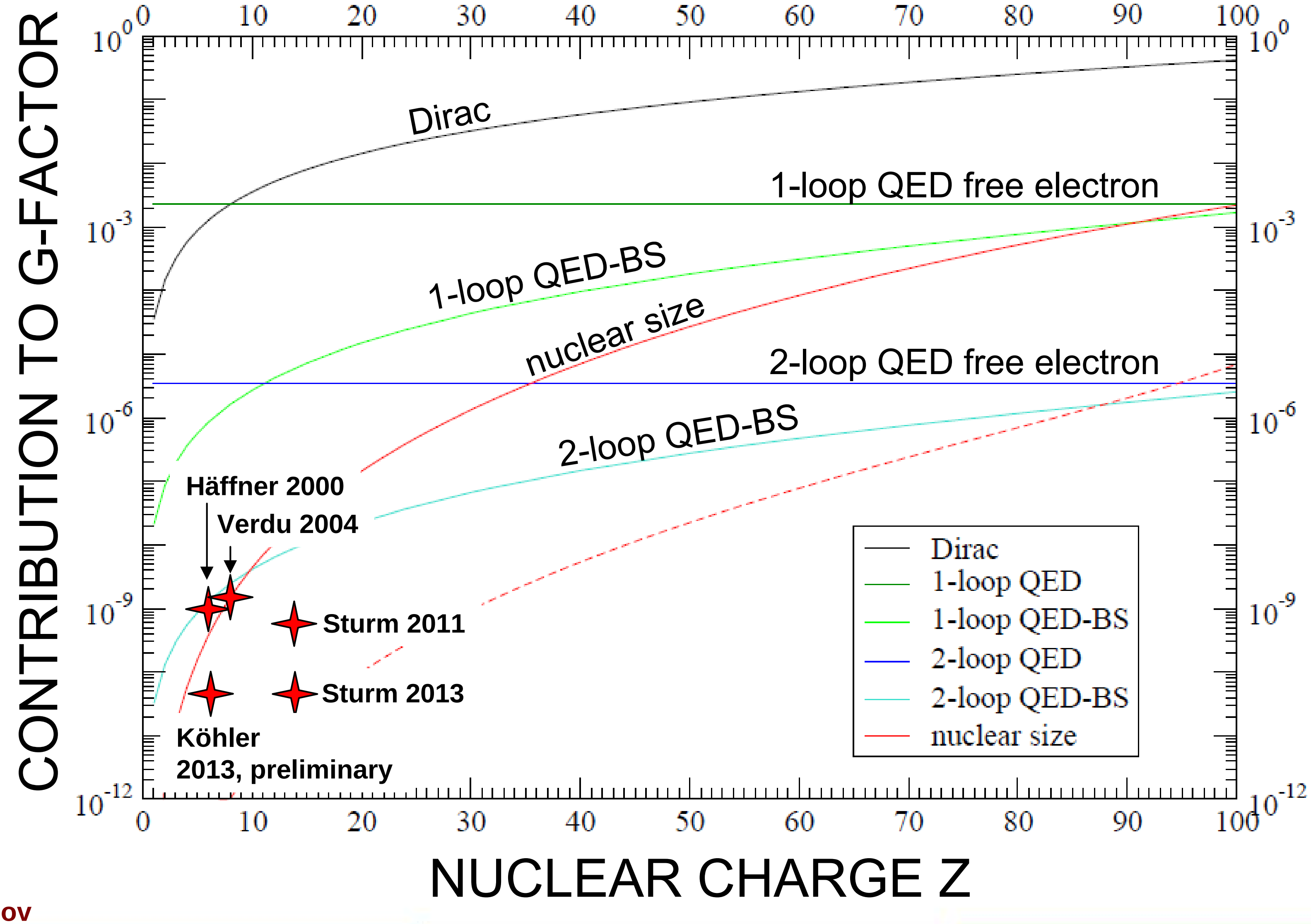
$g_J(^{12}C^{5+})$ = 2.001 041 590 18 (3) theoretical value
$g_J(^{12}C^{5+})$ = 2.001 041 596 4 (10)(44) our measurement

$g_J(^{16}O^{7+})$ = 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)

Bound-electron g-factor

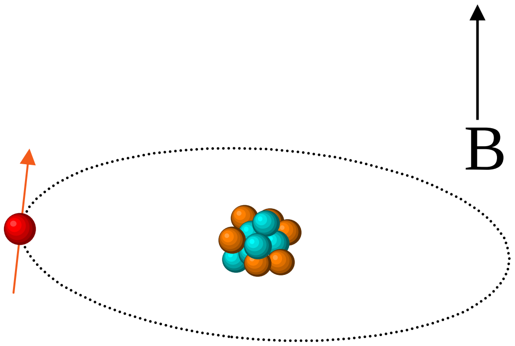


Ref.:
D. Glazov

Determination of electron mass

Larmor precession frequency of the bound electron:

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



Ion cyclotron frequency:

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

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

→ **determination of electron mass**

theory as input parameter

our measurement

Determination of the electron mass from g-factor measurements on H-like carbon $^{12}C^{5+}$ and oxygen $^{16}O^{7+}$

$^{12}C^{5+}$ g-factor measurement

$$\boxed{m_e(^{12}C^{5+}) = 0.000\,548\,579\,909\,32\,(29)\ \mathrm{u}}$$

$^{16}O^{7+}$ g-factor measurement

$$\boxed{m_e(^{16}O^{7+}) = 0.000\,548\,579\,909\,60\,(41)\ \mathrm{u}}$$

Van Dyck et al.,
comparison of cycl. frequencies $\nu_e/\nu(C^{6+})$

$$\boxed{m_e(\mathrm{UW}) = 0.000\,548\,579\,911\,10\,(120)\ \mathrm{u}}$$

Outlook:

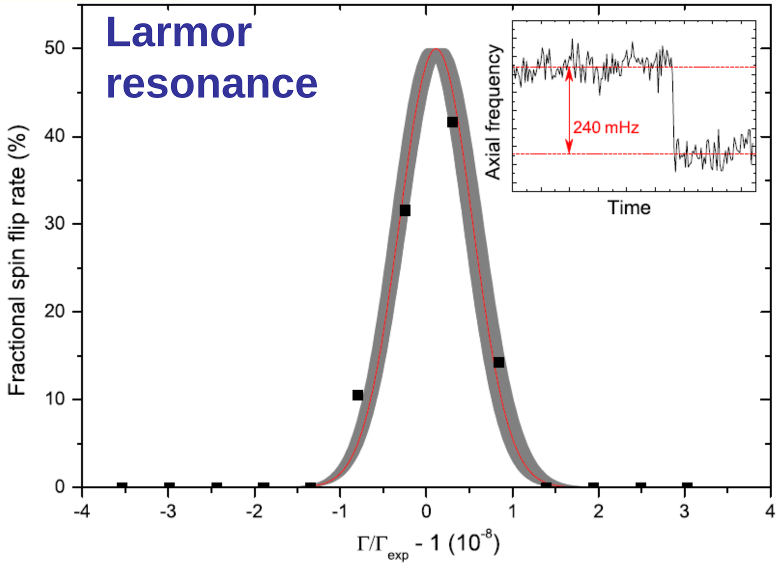
1) Improved measeurement on carbon C^{5+}, work in progress by F. Köhler and S. Sturm
2) measurements on lighter ions, e.g. $^4He^{1+}$

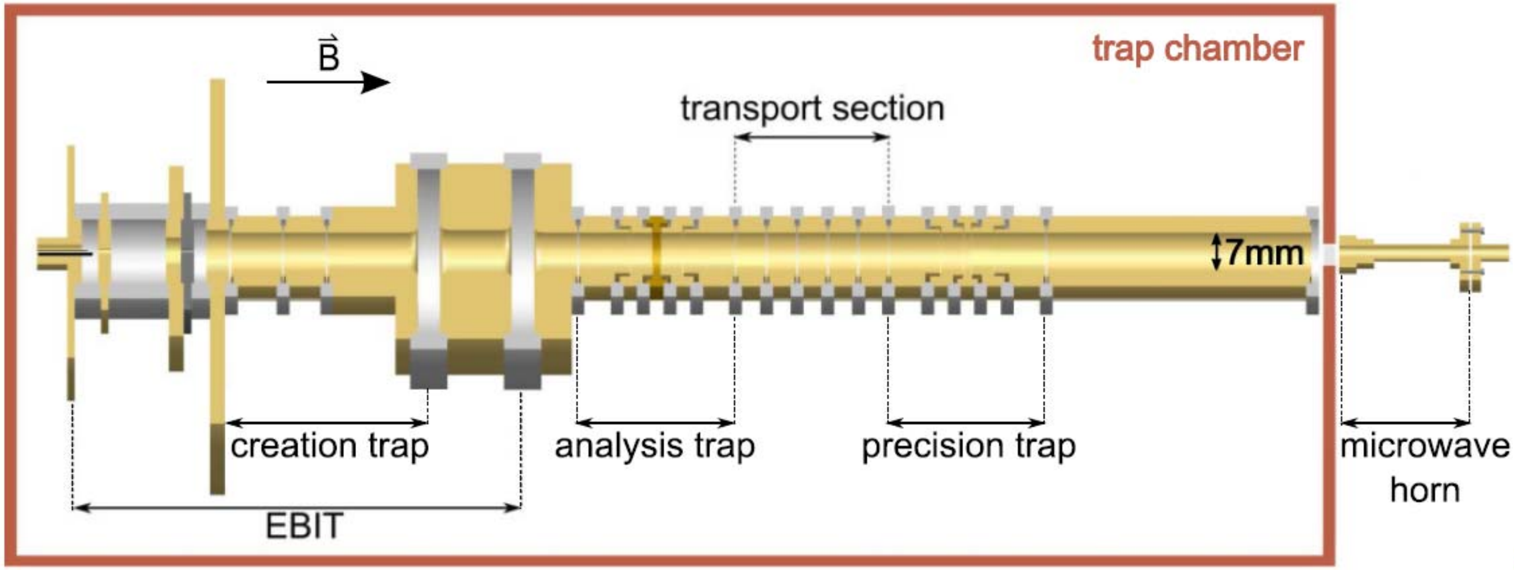
Bound electron magnetic moment measurement on lithium-like silicon $^{28}\mathrm{Si}^{11+}$

$g_{exp}(^{28}\mathrm{Si}^{11+})$ = 2.000 889 889 9(21)
$g_{theo}(^{28}\mathrm{Si}^{11+})$ = 2.000 889 909 (51)

theoretical calculations by D.A. Glazov,
A.V. Volotka, V.M. Shabaev

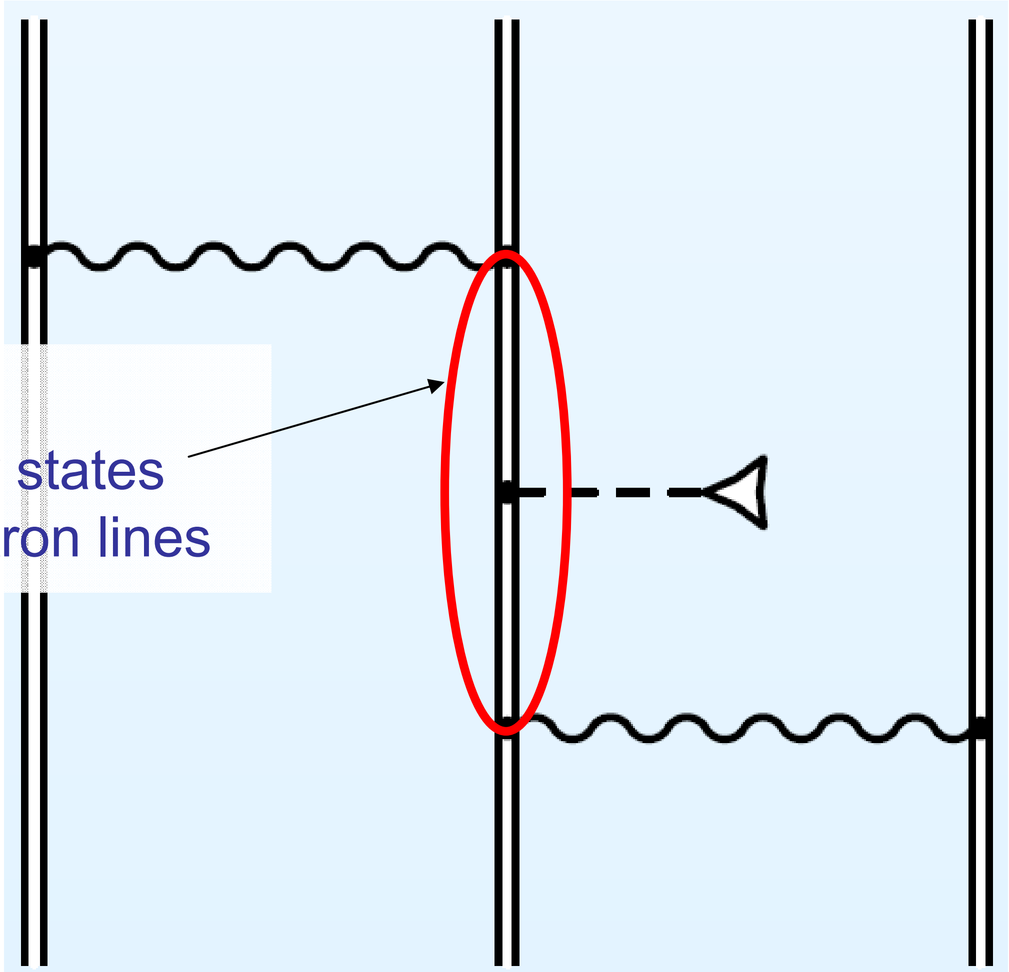
Precision test of
- electron-electron interaction
- screened QED contributions





Ref.:
A. Wagner et al.
PRL 110, 033003 (2013)

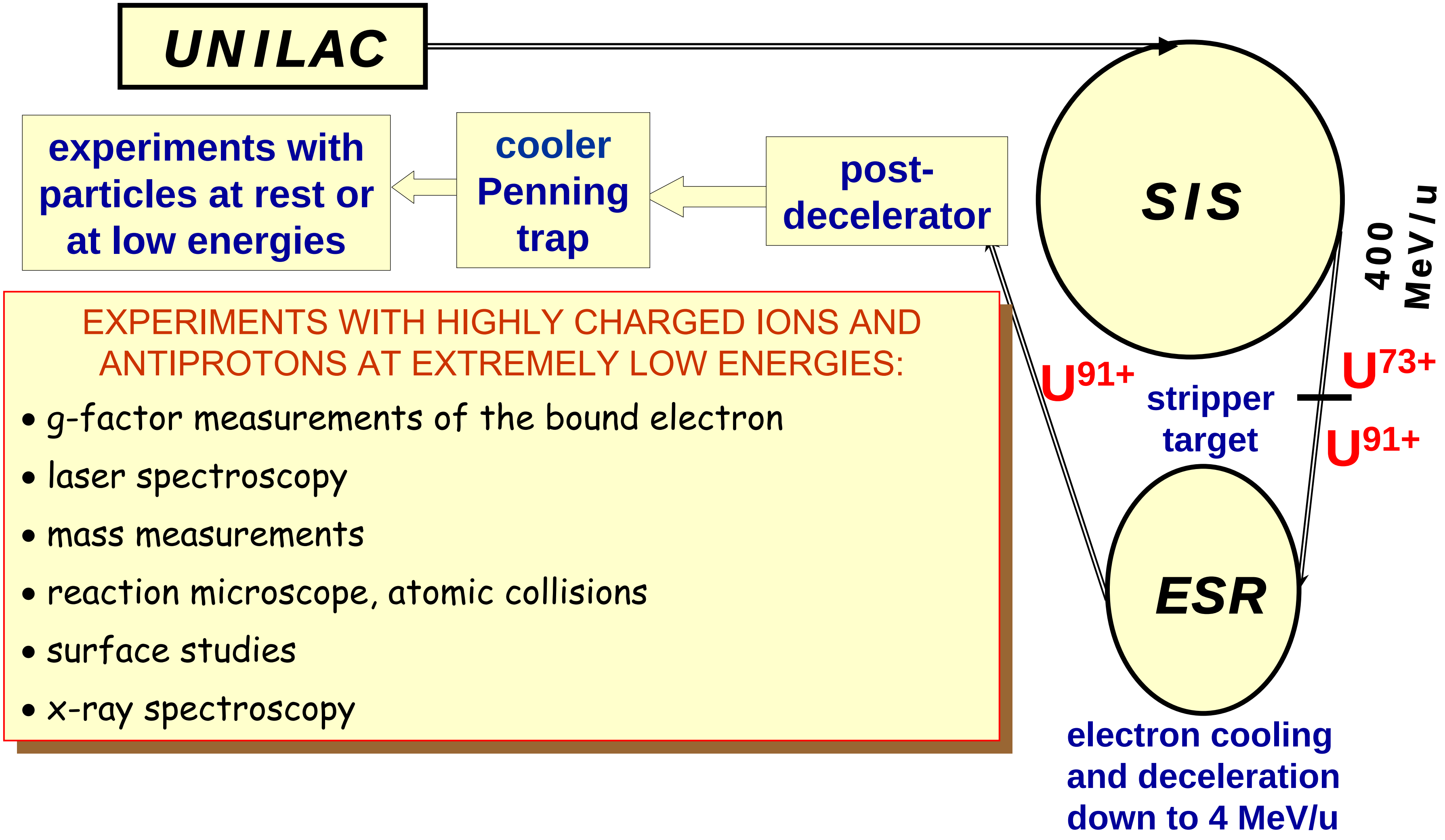
Dirac sea: contribution of negative energy states to bound electron magnetic moment in Li-like HCI



integration over
negative energy states
for internal electron lines

Ref.:
D. Glazov

HITRAP at the ESR storage ring / GSI



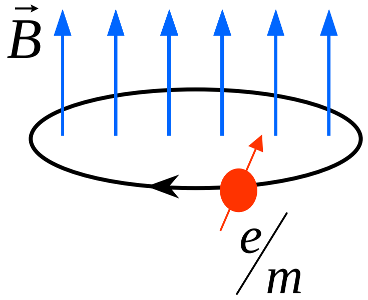
EXPERIMENTS WITH HIGHLY CHARGED IONS AND ANTIPROTONS AT EXTREMELY LOW ENERGIES:

- g-factor measurements of the bound electron
- laser spectroscopy
- mass measurements
- reaction microscope, atomic collisions
- surface studies
- x-ray spectroscopy

Determination of the proton g-factor

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

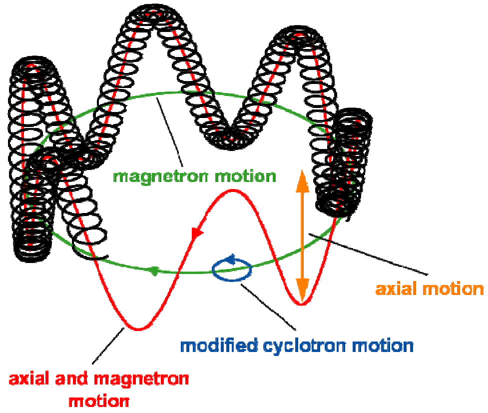
Cyclotron frequency



$$\omega_c = \sqrt{\omega_+^2 + \omega_-^2 + \omega_z^2}$$

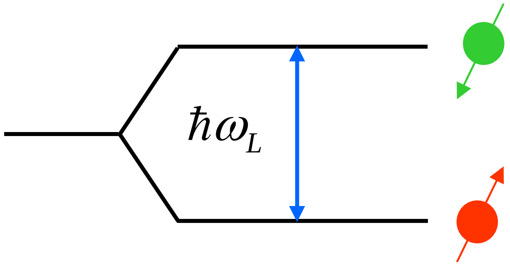
$$\omega_+ \approx 2\pi \cdot 29\,\text{MHz}$$
$$\omega_z \approx 2\pi \cdot 690\,\text{kHz}$$
$$\omega_- \approx 2\pi \cdot 8.5\,\text{kHz}$$

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

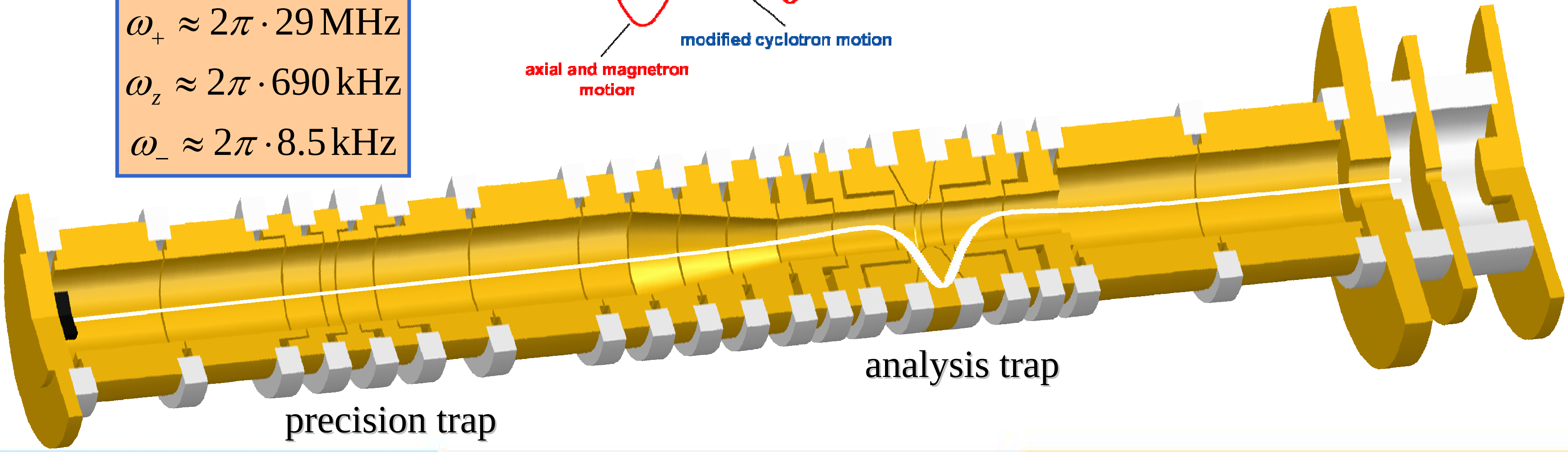


$$\omega_L = g\frac{e}{2m_p} B$$

Larmor frequency



$$\omega'_z(\uparrow) - \omega'_z(\downarrow) = \Delta\omega_z$$



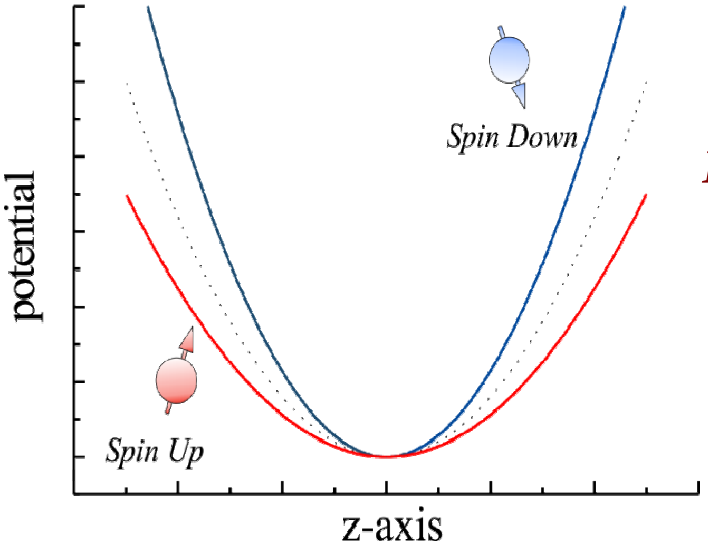
A single trapped proton and the continuous Stern-Gerlach effect

axial frequency shift due to spinflip:

$$\boxed{\Delta\nu_z \approx \frac{1}{2\pi^2}\frac{\mu_z B_2}{m\nu_z}}$$

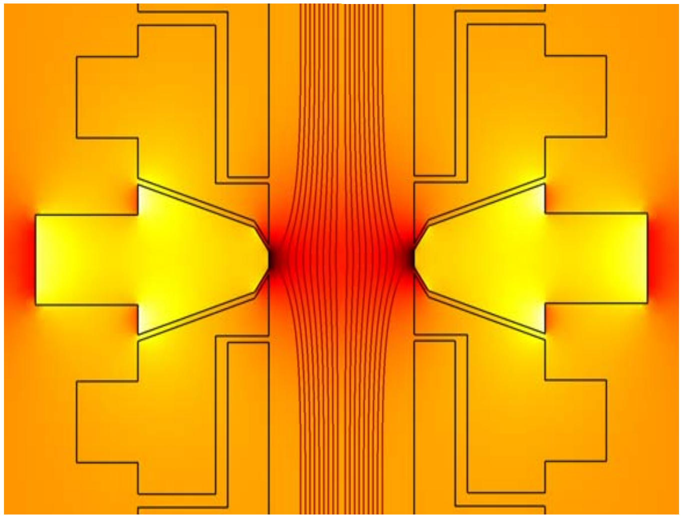
⇩

Proton measurement is 10 000 times harder compared to electron g-2 measurement.



B_2 = 0.3 T/mm²

$\Delta\nu_z$= 190 mHz



First Larmor resonance curve of a single proton in the Penning trap

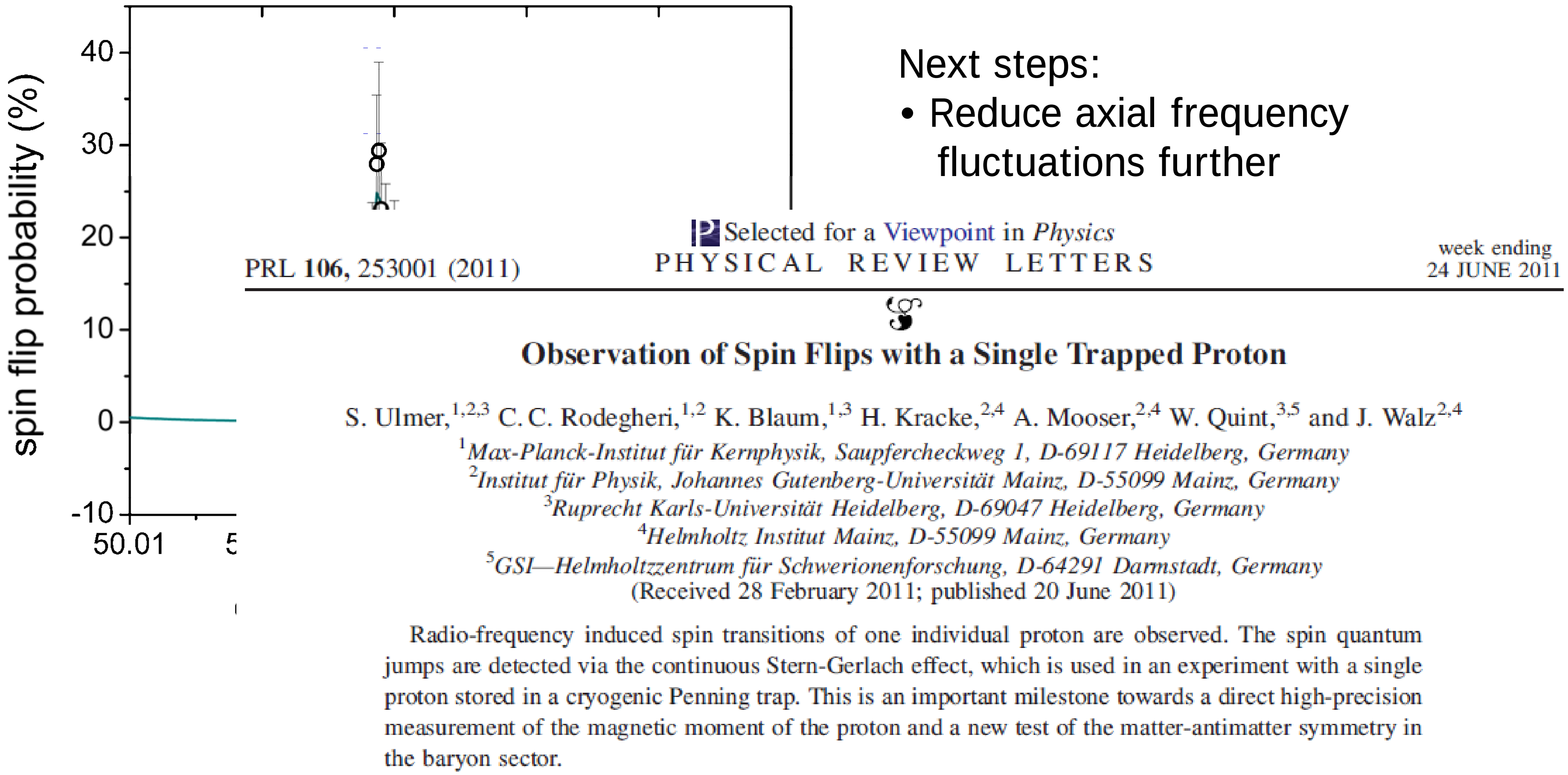
- ✓ Axial temperature reduced
- ✓ Larmor resonance narrower

$$\frac{\Delta\nu_L}{\nu_L} = 1.2\cdot 10^{-6}$$

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

Next steps:

- Reduce axial frequency fluctuations further



Selected for a Viewpoint in *Physics*

PRL **106,** 253001 (2011)

PHYSICAL REVIEW LETTERS

week ending
24 JUNE 2011

Observation of Spin Flips with a Single Trapped Proton

S. Ulmer,[1,2,3] C. C. Rodegheri,[1,2] K. Blaum,[1,3] H. Kracke,[2,4] A. Mooser,[2,4] W. Quint,[3,5] and J. Walz[2,4]

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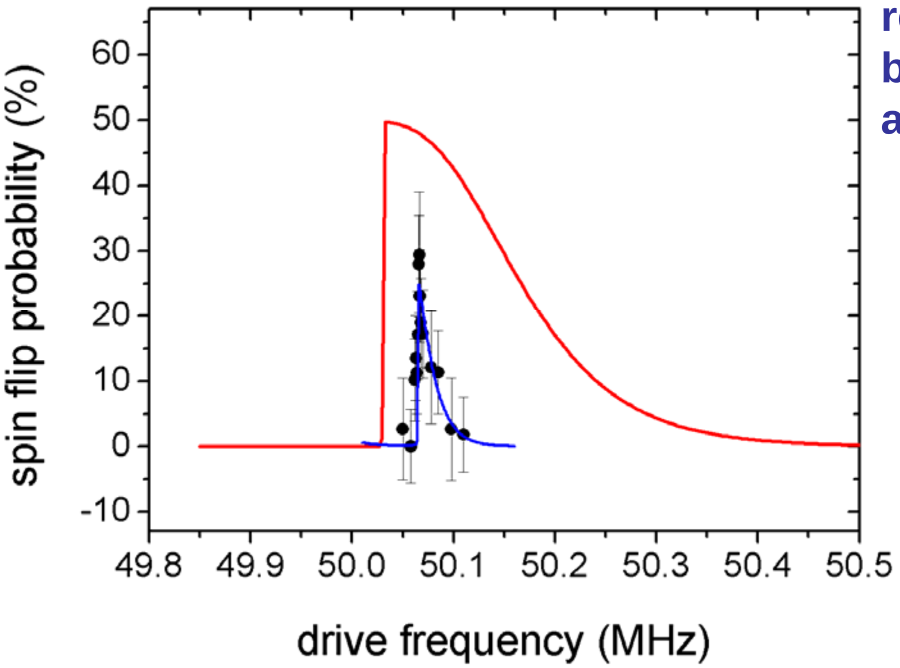
[2]*Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[3]*Ruprecht Karls-Universität Heidelberg, D-69047 Heidelberg, Germany*
[4]*Helmholtz Institut Mainz, D-55099 Mainz, Germany*
[5]*GSI—Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*

(Received 28 February 2011; published 20 June 2011)

Radio-frequency induced spin transitions of one individual proton are observed. The spin quantum jumps are detected via the continuous Stern-Gerlach effect, which is used in an experiment with a single proton stored in a cryogenic Penning trap. This is an important milestone towards a direct high-precision measurement of the magnetic moment of the proton and a new test of the matter-antimatter symmetry in the baryon sector.

Proton g-factor measurement with and without active feedback cooling

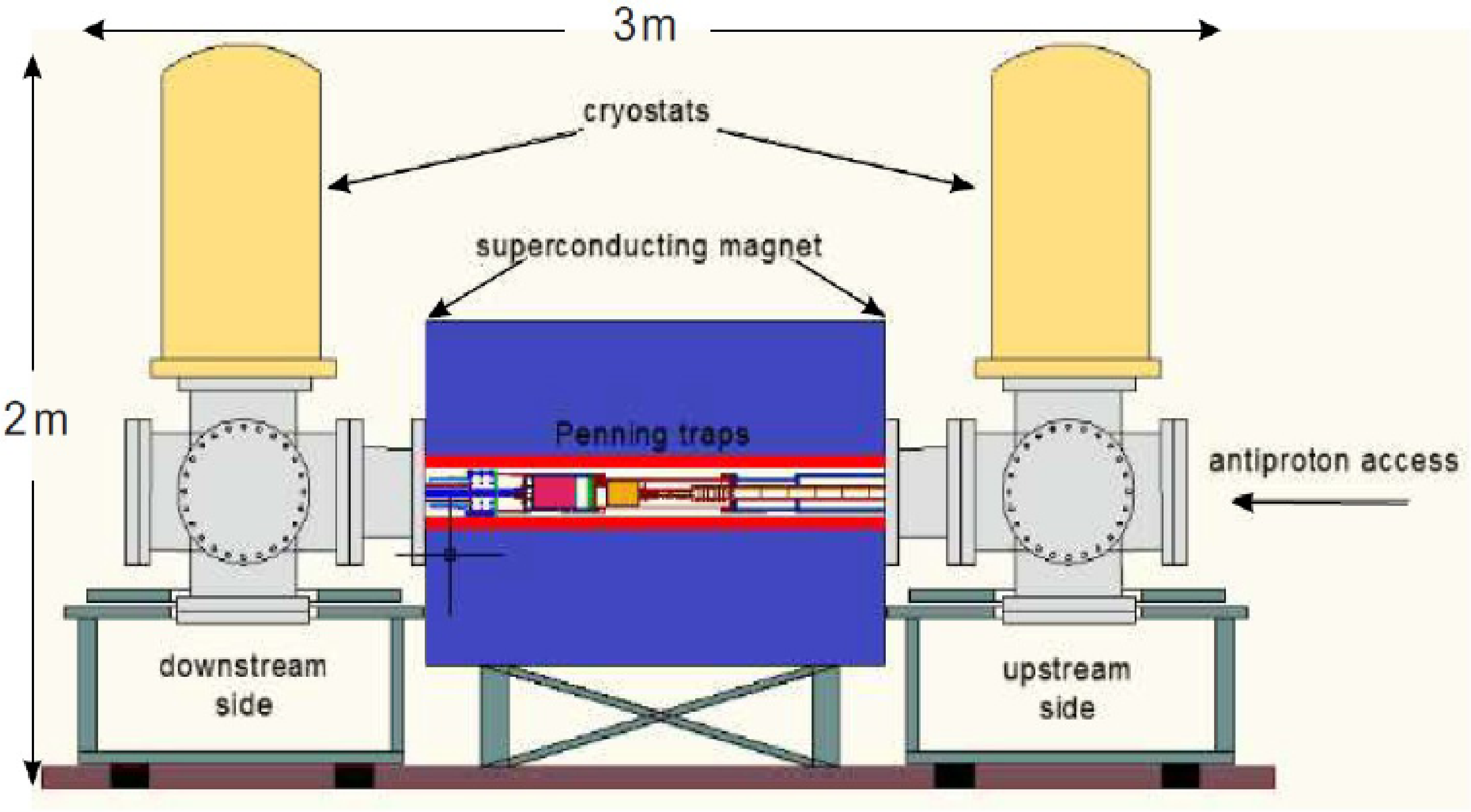


reduction of axial temperature
by application of
active electronic feedback

$$g_p = 5.585696\ (50)$$

Ref.:
C. Rodegheri et al., NJP 2012

Baryon-Antibaryon Symmetry Experiment – The BASE Collaboration at AD / CERN



Acknowledgements

- ✓Group at the institute of physics - Mainz
- ✓Group of Klaus Blaum at MPIK Heidelberg
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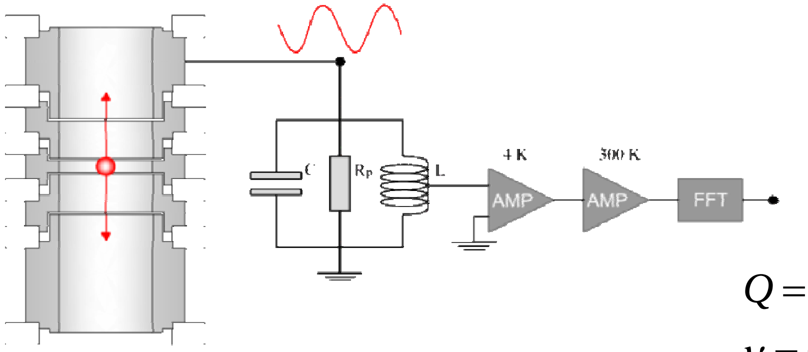
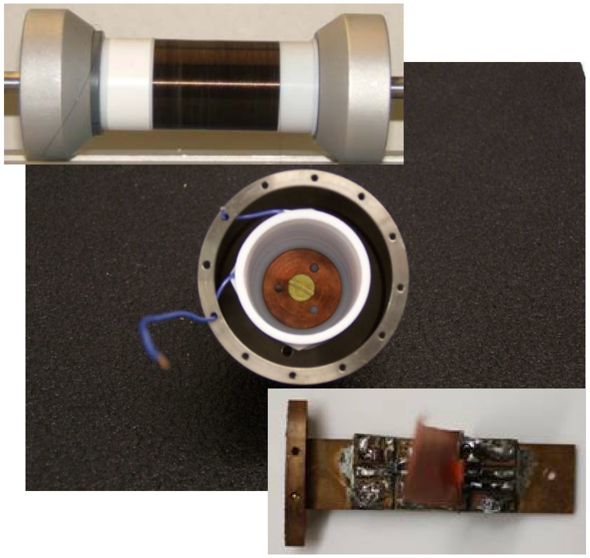
International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

Thank you for your attention !

Electronic detection of a single ion by resonance circuit





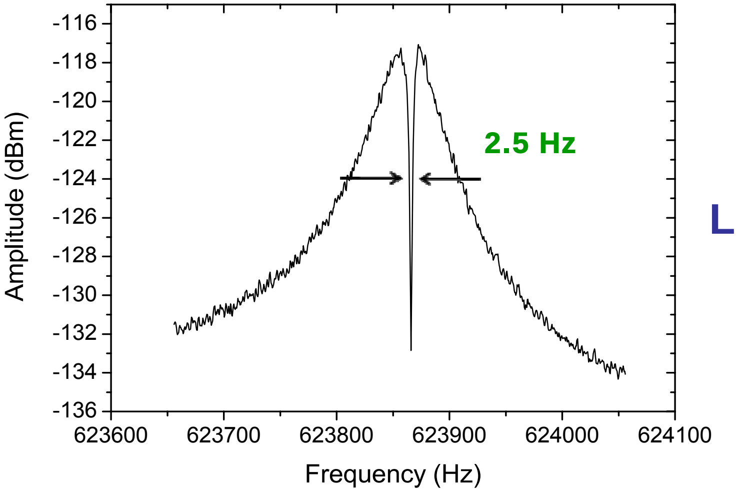
$$Q = 5600$$

$$\nu = 680\ \text{kHz}$$

$$R_p = 36\ \text{M}\Omega$$

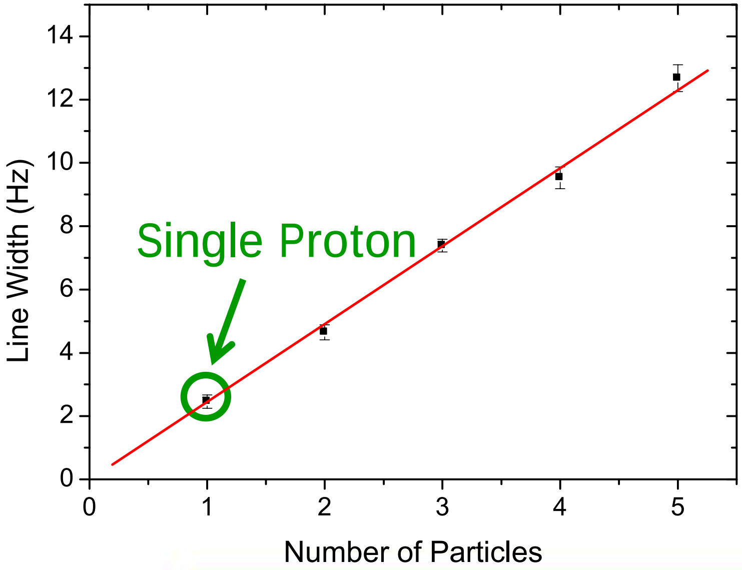
$$e_n = 1.3\ \text{nV}/\sqrt{\text{Hz}}$$

- Particle acts as a perfect short



Line width

$$\delta\nu_z \propto N_p$$

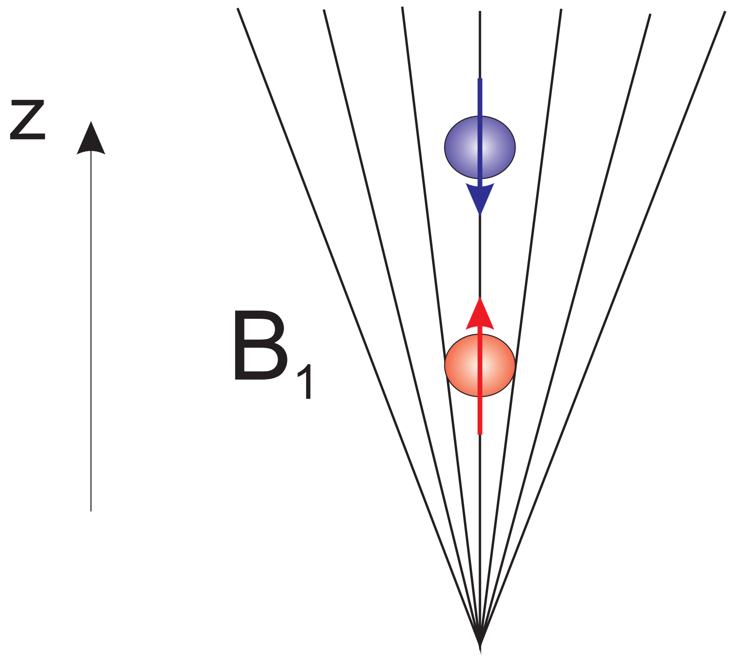


Ref.:
A. Mooser

Continuous Stern-Gerlach effect: Determination of spin direction

CLASSICAL STERN-GERLACH

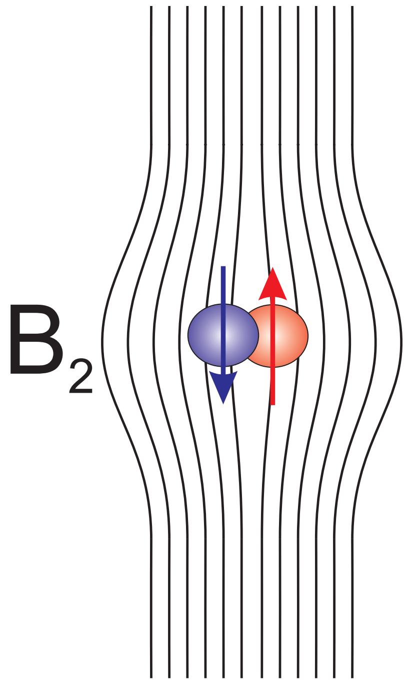
SEPARATION IN POSITION SPACE



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

CONTINUOUS STERN-GERLACH

SEPARATION IN FREQUENCY SPACE



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

Quantum jumps of a single HCI in a Penning trap