MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Measurements of the bound-electron g factor in highly charged ions: Testing fundamental physics

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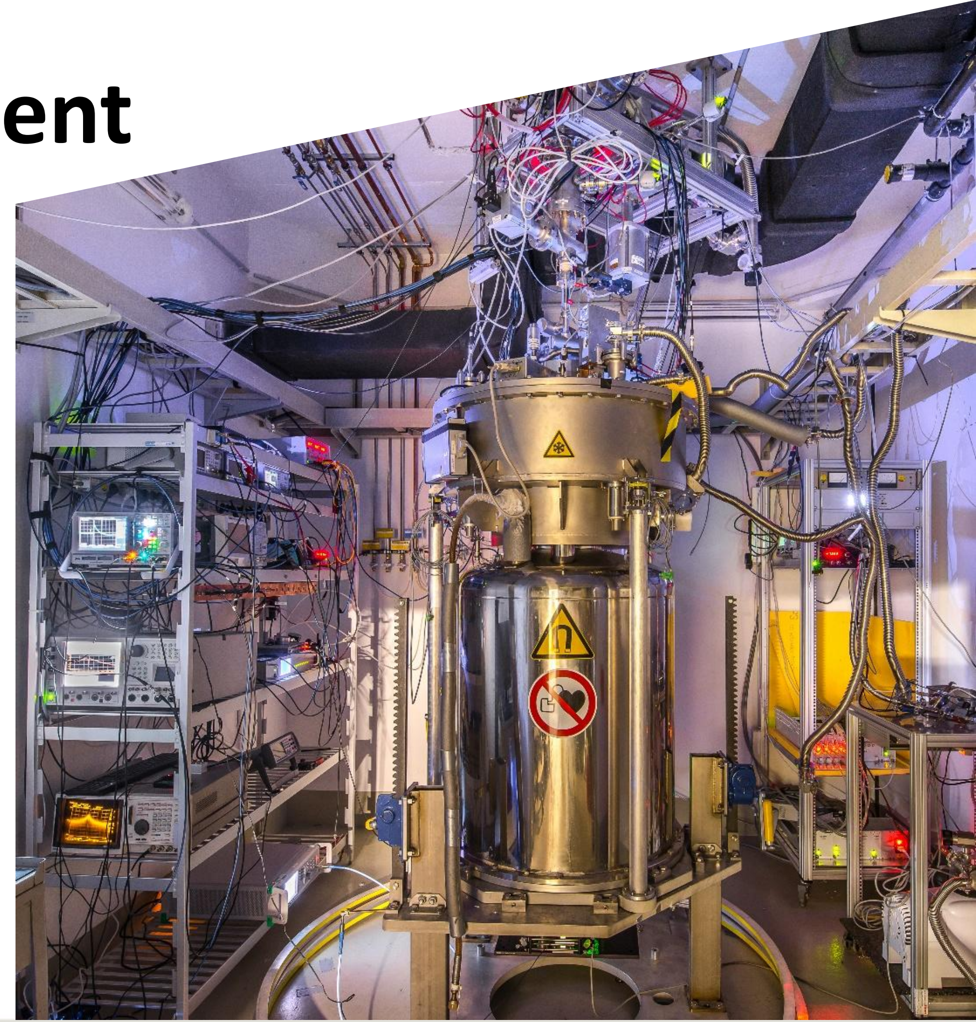
The ALPHATRAP experiment

for **measurements of the bound-electron g factor** on simple, calculable ions

- cryogenic Penning trap with 4 T magnet
- access to externally produced HCIs
  - HC-EBIT ("Mini-EBIT") $Z_{\max} \leq 14$
  - Heidelberg-EBIT $Z_{\max} \leq 55$
  - Hyper-EBIT (in prep.) $Z_{\max} \geq 82$
- room temperature beamline separated from the trap by cryogenic valve
  - pressure below 10^{-16} mbar
  - weeks of storage without recombinations



Precise measurements of the g-factor (magnetic moment)

HD$^+$

- Hyperfine spectroscopy
  - probe fundamental spin-spin interaction theory
  - Extraction of fundamental constants
- rovibrational laser spectroscopy
  - for future matter-antimatter comparisons

Session 16

- M. Bohman

C. M. König *et al.*
PRL **134**, 163001 (2025)
PRL **136**, 143002 (2026)

$^{12}C^{5+}$

- Extraction of fundamental constants (m_e)

current work in progress

F. Heiße *et al.*
PRL **131**, 253002 (2023)

$^{20/22}Ne^{9+}$

- resolve the intricate effects stemming from the nuclear differences
- determine charge-radius differences
- set constraints on new physics

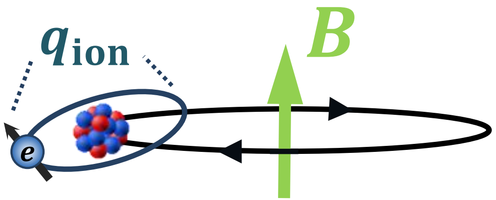
T. Sailer *et al.*
Nature **606**, 479 (2022)

$^{118}Sn^{49+}$

- stringent high-field tests of QED
- extract nuclear root-mean-square radii

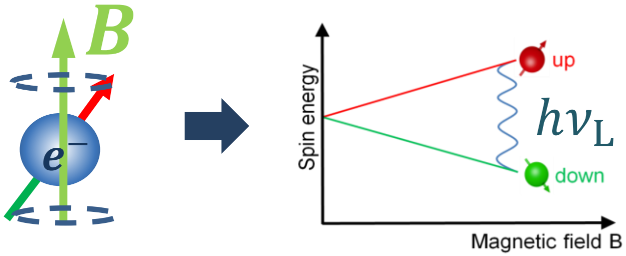
J. Morgner *et al.*
Nature **622**, 53 (2023)
Science **388**, 945 (2025)
PRL **134**, 123201 (2025)

General measurement principle



$$2\pi\,\nu_c = \frac{q_{\text{ion}}}{m_{\text{ion}}} B$$

Measure the free cyclotron frequency to determine magnetic field



$$2\pi\,\nu_L = \frac{g}{2}\frac{e}{m_{\text{e}}} B$$

Probe the Larmor frequency in the same magnetic field

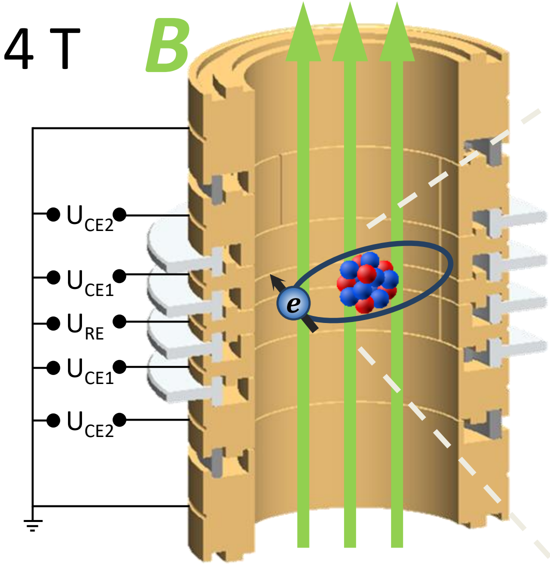
$$\Gamma = \frac{\nu_{\text{L}}}{\nu_{\text{c}}}$$

is measured

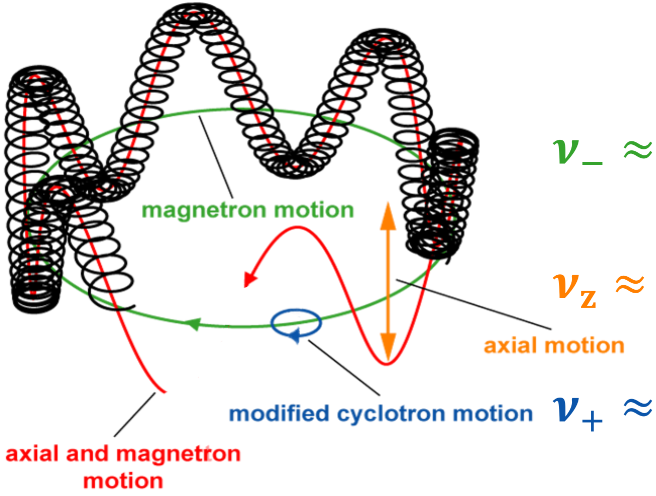
$$g = 2\frac{\nu_{\text{L}}}{\nu_{\text{c}}}\frac{q_{\text{ion}}}{e}\frac{m_{\text{e}}}{m_{\text{ion}}}$$

External input parameters

Single-Ion Penning trap



- Charged particle trapped by static B- and E- field



$$\nu_- \approx 9\ \mathrm{kHz} \qquad \propto \frac{U_0}{B_0}$$

$$\nu_z \approx 670\ \mathrm{kHz} \qquad \propto \sqrt{\frac{qU_0}{m}}$$

$$\nu_+ \approx 26\ \mathrm{MHz} \qquad \propto \frac{q}{m} B_0$$

- Three independent harmonic motions with eigenfrequencies
- Additionally, the Larmor (spin precession) frequency:

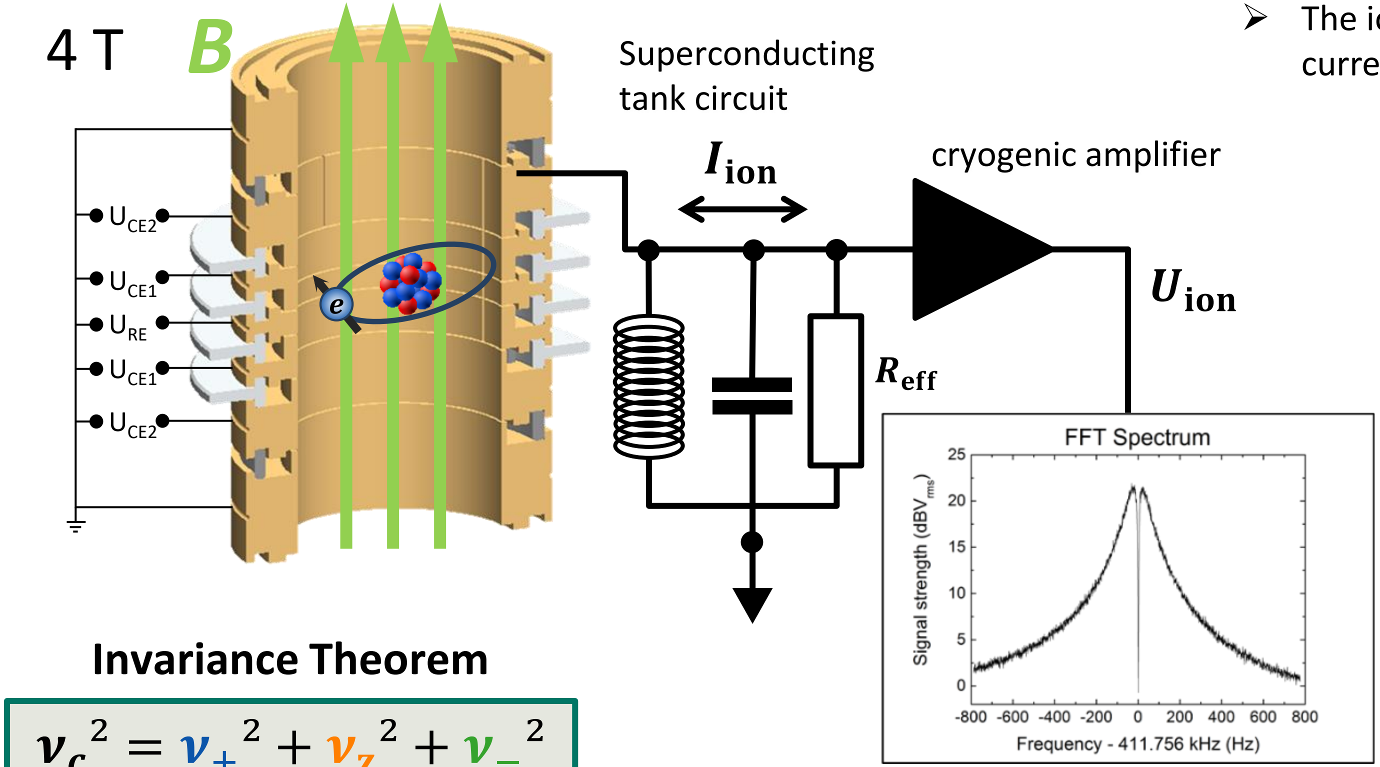
$$\nu_{\mathrm{L,e}} \approx 112\ \mathrm{GHz} \qquad \propto g$$

Invariance Theorem

$$\boxed{\nu_c{}^2 = \nu_+{}^2 + \nu_z{}^2 + \nu_-{}^2}$$

Ion detection

- The ion induces small image charge currents ~10 fA



Invariance Theorem

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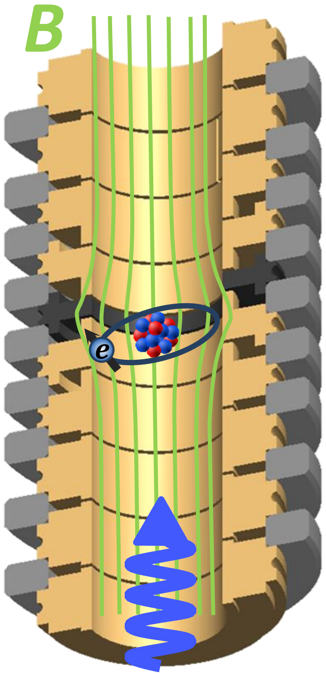
Continuous Stern-Gerlach Effect

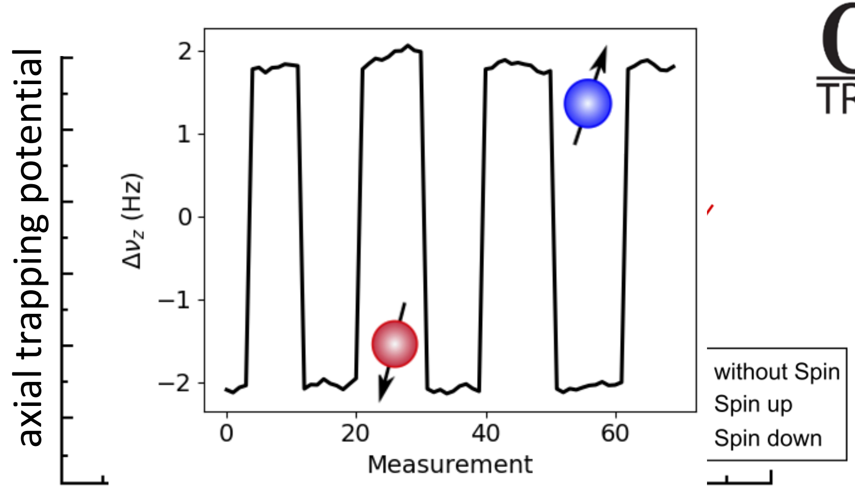


Analysis Trap (AT)

ferromagnetic ring

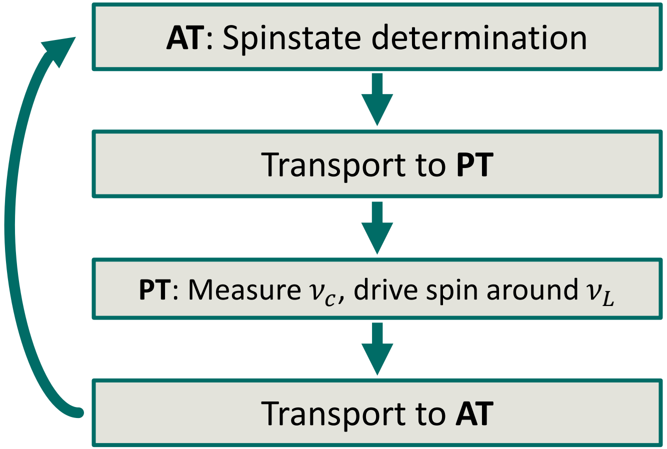
Magnetic field inhomogeneity

Microwave access



- ➢ Magnetic bottle makes the axial frequency spinstate dependent
- ➢ Driving a spinflip results in a changed axial frequency
- ➢ Spin-flip is driven by resonant microwave excitation

Trap Setup & Measurement Cycle

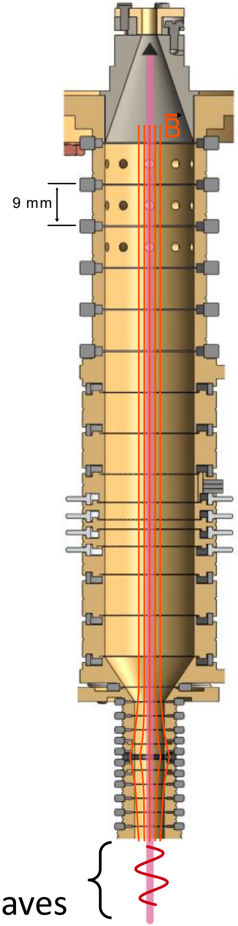


AT: Spinstate determination

Transport to **PT**

PT: Measure ν_c, drive spin around ν_L

Transport to **AT**



Capture electrodes:
- Capture HCI
- Ion storage

Precision trap (PT):
- Large radius to reduce syst. shifts
- Measurement of ν_c at ~ 4 T hom. mag. field
- Spin flips induced by MW

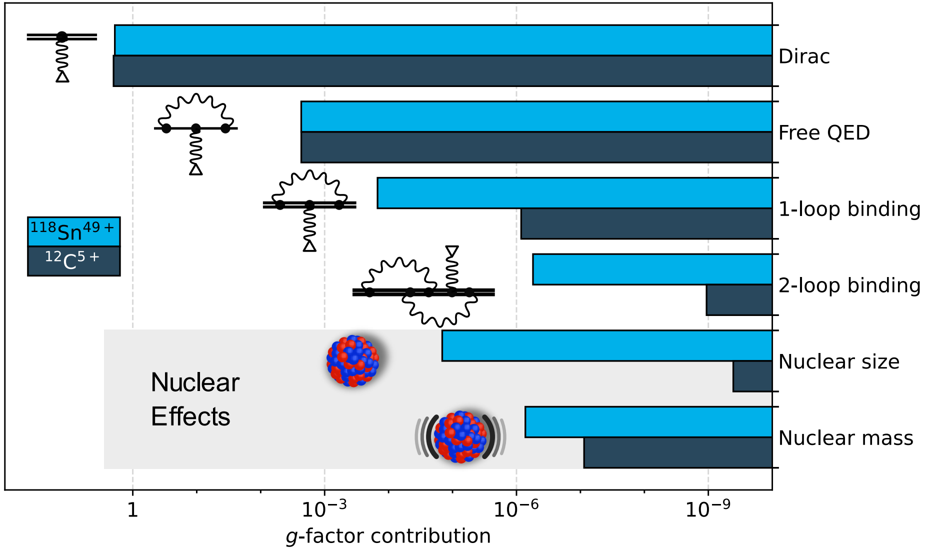
Analysis trap (AT):
- Ferromag. CoFe ring creates inhom. Field region
- Detection of spin orientation

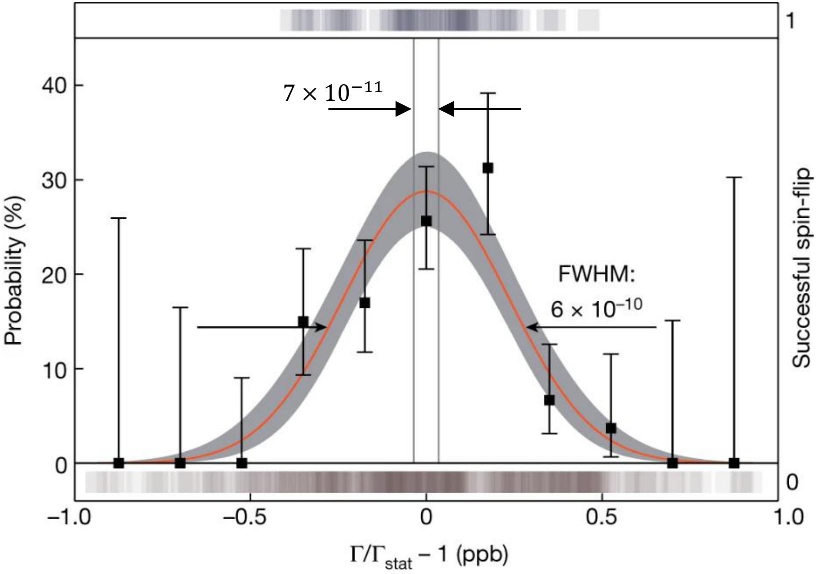
- Laser
- Microwaves

Single-ion measurement result: The g factor of hydrogenlike $^{118}\mathrm{Sn}^{49+}$

$$g_{\mathrm{exp}} = 1.910\,562\,059\,0(9)$$

$$g_{\mathrm{theo}} = 1.910\,561\,975(39)$$





J. Morgner *et al.* *Nature* **622**, 53 (2023)

B. Sikora *et al.* PRL **134**, 132001 (2024)

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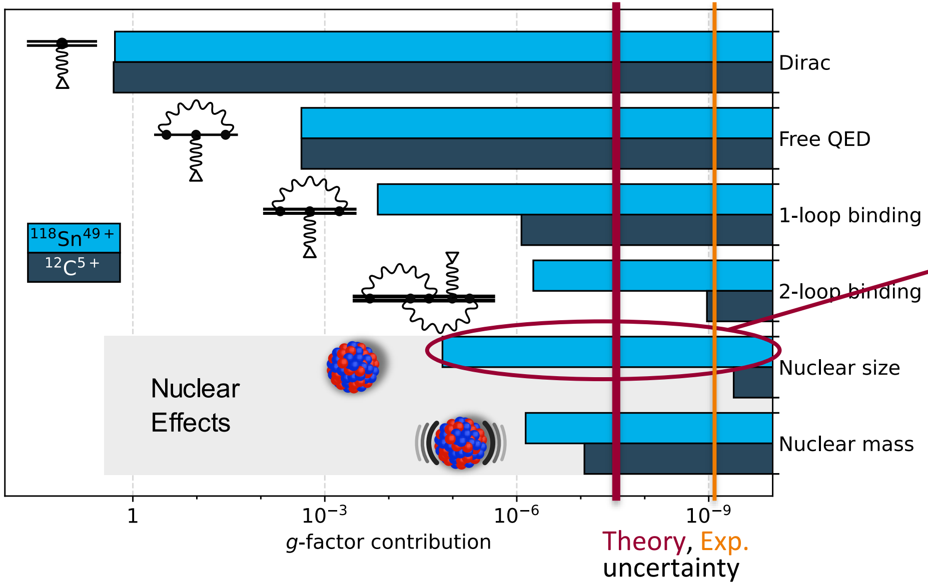
Complete Two-Loop QED Calculations



allows determining the absolute charge radius of Sn with a precision of about 0.2%!

Direct *g*-factor difference measurement

(Future prospects)

- Extraction of high precision rms nuclear charge radius differences:

T. Sailer *et al.*
Nature **606**, 479 (2022)

20, 22-Neon: $0.0530(34)\ \mathrm{fm} \rightarrow 0.0533(4)\ \mathrm{fm}$

I. Angeli, K.P. Marinova
At. Data Nucl. Data Tables **99**, 69 (2013)

12, 14-Carbon: $0.0323(90)\ \mathrm{fm}$

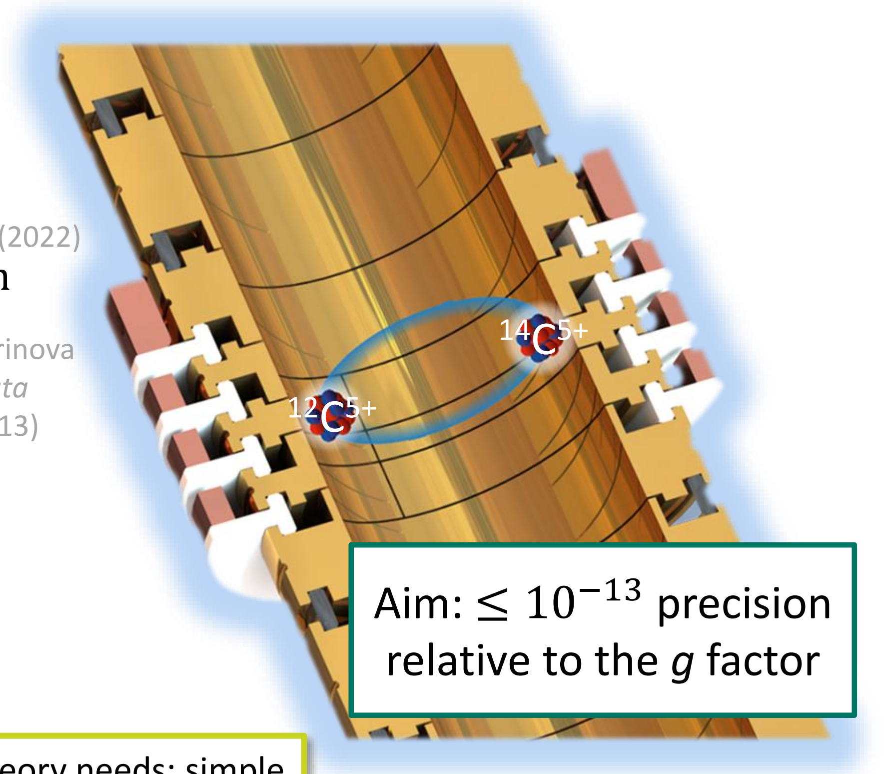
$$3.1\ \mathrm{am} > \Delta\delta\langle r^2\rangle \geq 0.7\ \mathrm{am}$$

- Uniqueness of carbon:

We need: stable isotopes without nuclear spin

Measurements of similar precision in sight, within COALA (W. Nörtershäuser) at TU Darmstadt (1.4 am for ^{12,13}C)

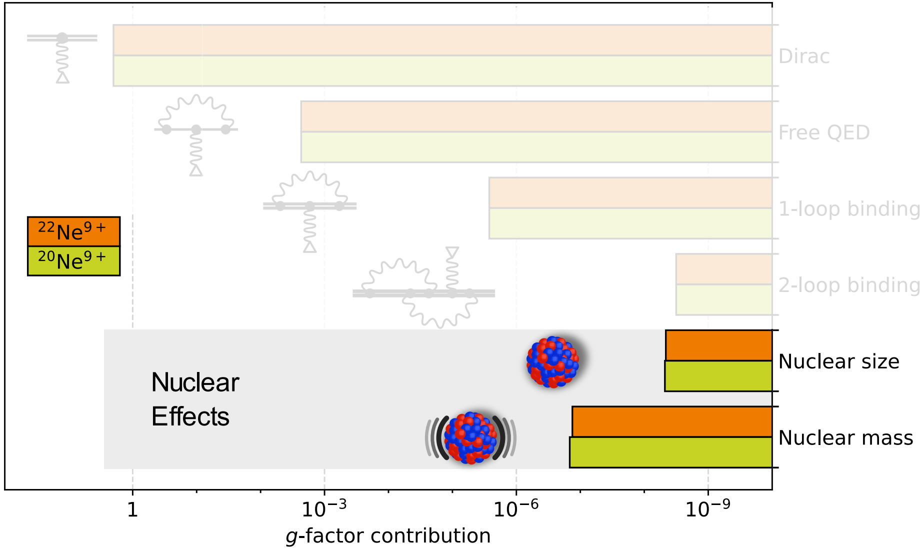
Theory needs: simple system to be precisely calculable



Aim: $\leq 10^{-13}$ precision relative to the *g* factor

Towards Δg measurements

Comparison of isotopes (equal Z)



Direct g-factor difference measurement

- Two ions in a Penning-Trap locked on a common magnetron orbit

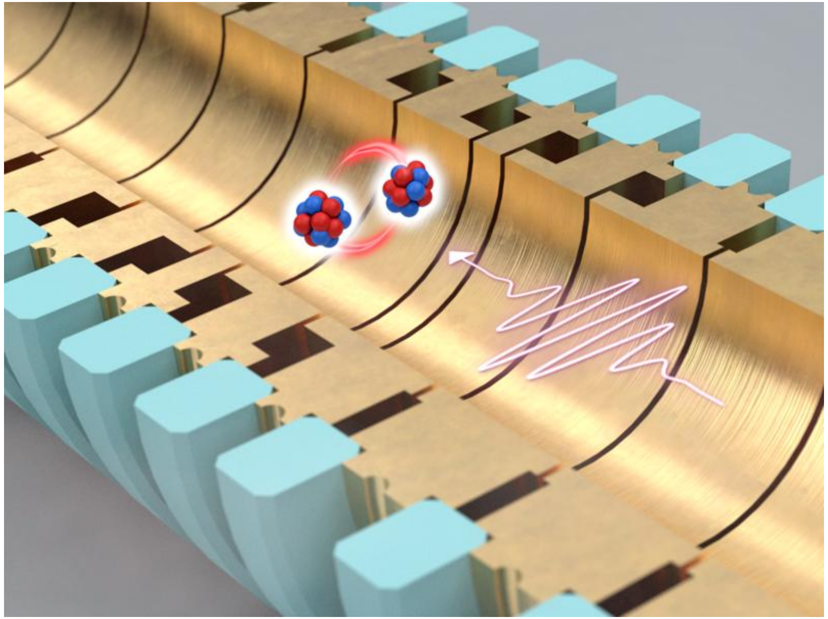
S. Rainville *et al.*
Science **303**, 334 (2004)

- Measure the g-factor difference in the decoherence-free configuration

- Achieve high accuracy compared to a "typical" g-factor measurement

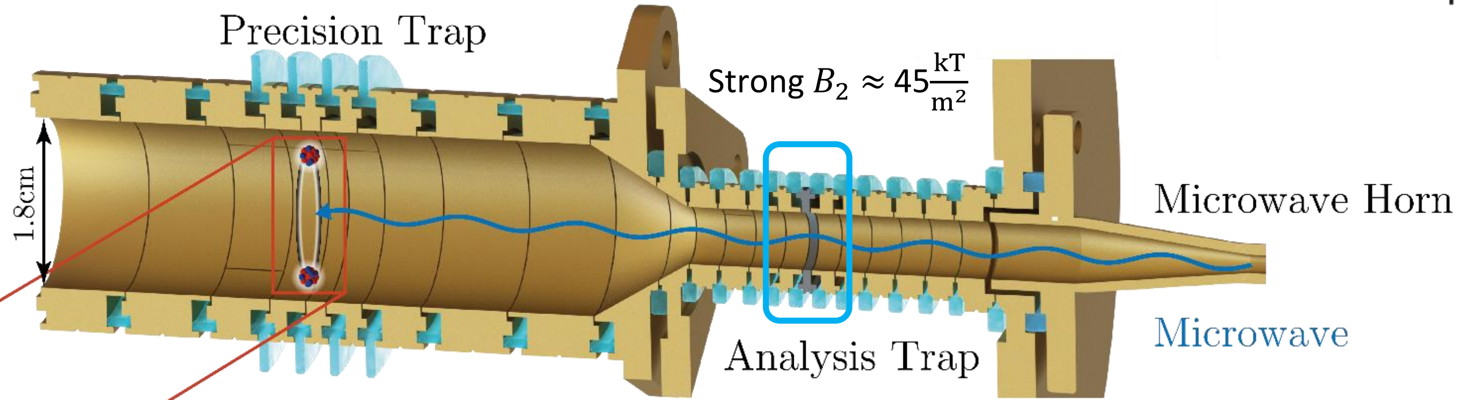
$$\frac{g_1}{2}\frac{e}{m_\mathrm{e}}B - \frac{g_2}{2}\frac{e}{m_\mathrm{e}}B = \omega_{\mathrm{L},1} - \omega_{\mathrm{L},2}$$

$$\Delta g \frac{e}{2m_\mathrm{e}}B = \Delta\omega_\mathrm{L}$$

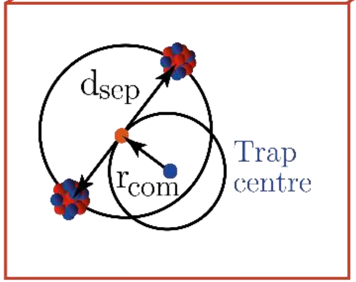


T. Sailer *et al.*
Nature **606**, 479 (2022)

About the Δg-measurement technique



Coupled ions motion (PT)



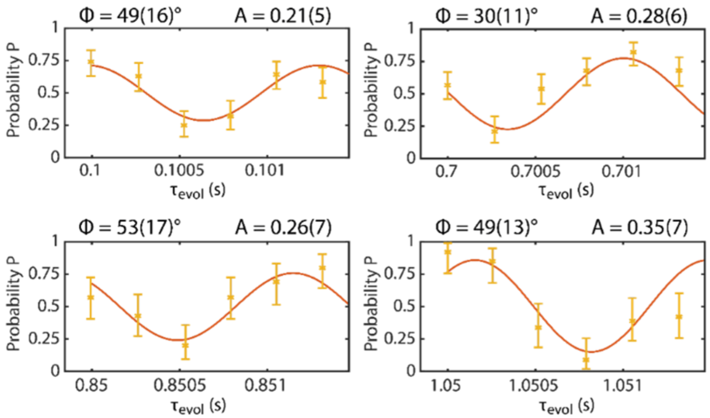
Step 1:
Spin-state determination of separated ions (AT).

Step 2:
Prepare the ions' coupled motion (PT).

Step 3:
Microwave irradiation at different evolution times (PT).

Step 4:
Determination of the accumulated phase.

Direct *g*-factor difference measurement

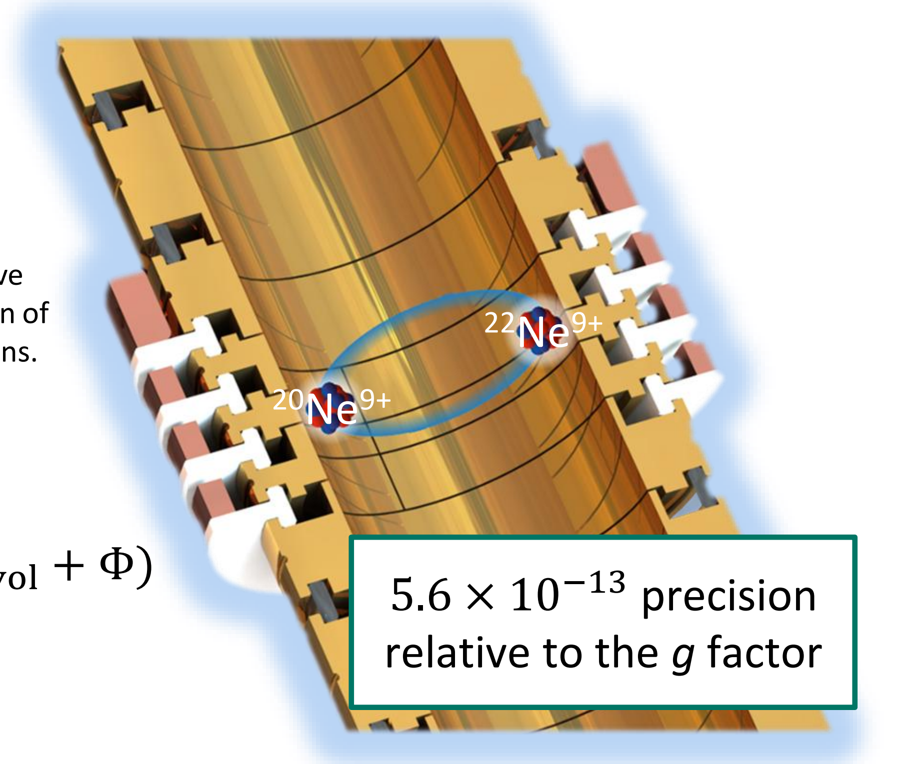


Data analysis:
Determine relative phase modulation of the individual spins.

$$P(t) = P(\downarrow,\downarrow) + P(\uparrow,\uparrow) = \frac{1}{2} + A\cos(\Delta\omega_L \tau_{\text{evol}} + \Phi)$$

Measure beating frequency of the two Larmor frequencies:

$$\Delta\omega_L = \omega_{\text{Ion 1}} - \omega_{\text{Ion 2}}$$



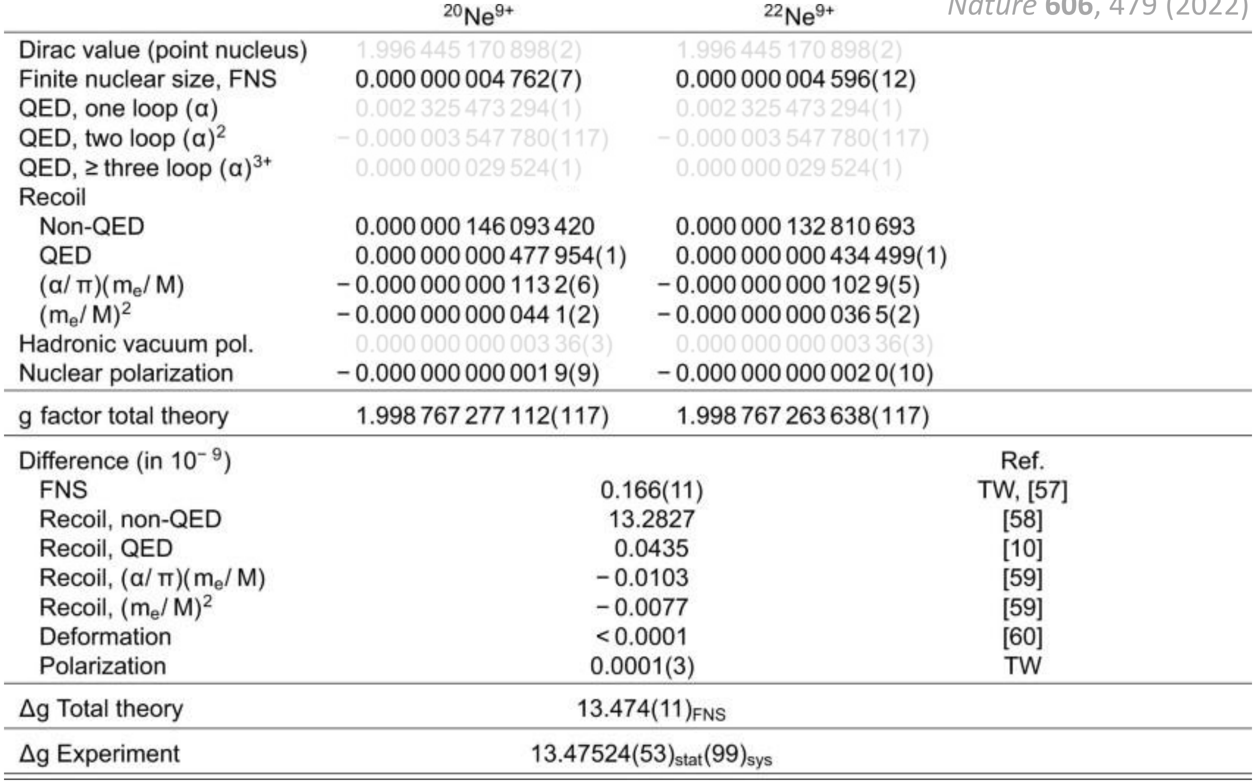
5.6×10^{-13} precision relative to the *g* factor

T. Sailer *et al.*
Nature **606**, 479 (2022)

Coupled-ions measurement result: The g factor difference of $^{20,22}\mathrm{Ne}^{9+}$

T. Sailer *et al.*
Nature **606**, 479 (2022)

- Perfect agreement with theory at 5 x 10^{-12} level!
- Confirmation of QED recoil contribution in g factors!
- Alternatively:
  Improve the precision of charge radii differences

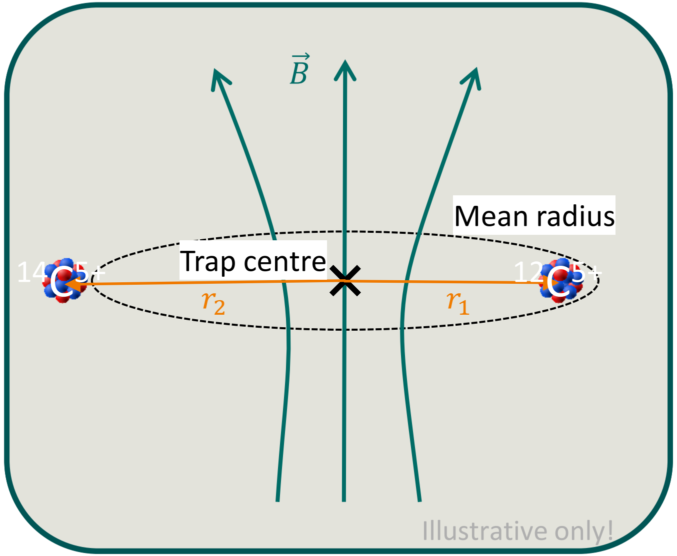


	$^{20}\mathrm{Ne}^{9+}$	$^{22}\mathrm{Ne}^{9+}$
Dirac value (point nucleus)	1.996 445 170 898(2)	1.996 445 170 898(2)
Finite nuclear size, FNS	0.000 000 004 762(7)	0.000 000 004 596(12)
QED, one loop (α)	0.002 325 473 294(1)	0.002 325 473 294(1)
QED, two loop $(\alpha)^2$	− 0.000 003 547 780(117)	− 0.000 003 547 780(117)
QED, ≥ three loop $(\alpha)^{3+}$	0.000 000 029 524(1)	0.000 000 029 524(1)
Recoil		
Non-QED	0.000 000 146 093 420	0.000 000 132 810 693
QED	0.000 000 000 477 954(1)	0.000 000 000 434 499(1)
$(\alpha/\pi)(m_e/M)$	− 0.000 000 000 113 2(6)	− 0.000 000 000 102 9(5)
$(m_e/M)^2$	− 0.000 000 000 044 1(2)	− 0.000 000 000 036 5(2)
Hadronic vacuum pol.	0.000 000 000 003 36(3)	0.000 000 000 003 36(3)
Nuclear polarization	− 0.000 000 000 001 9(9)	− 0.000 000 000 002 0(10)
g factor total theory	1.998 767 277 112(117)	1.998 767 263 638(117)

Difference (in 10^{-9})		Ref.
FNS	0.166(11)	TW, [57]
Recoil, non-QED	13.2827	[58]
Recoil, QED	0.0435	[10]
Recoil, $(\alpha/\pi)(m_e/M)$	− 0.0103	[59]
Recoil, $(m_e/M)^2$	− 0.0077	[59]
Deformation	< 0.0001	[60]
Polarization	0.0001(3)	TW
Δg Total theory	$13.474(11)_{\mathrm{FNS}}$	
Δg Experiment	$13.47524(53)_{\mathrm{stat}}(99)_{\mathrm{sys}}$	

What limits our precision?

- The spins do lose coherence at some point
- Larmor frequencies are affected by slightly different magnetic field
- 2 causes:
  - Magnetron imbalance: $r_2 > r_1$
  - Inhomogeneous B-field components

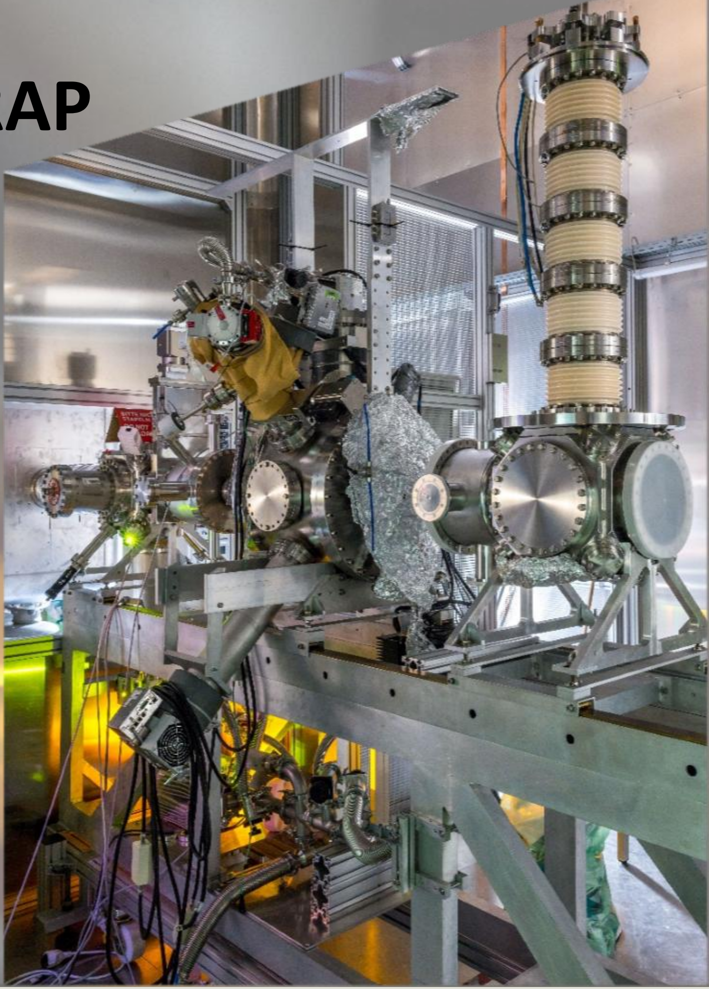


➢ Improve magnetic homogeneity with shimming coils

Future QED-tests at ALPHATRAP

- Specifications for the Hyper-EBIT:
  Design goal for the electron beam:
  300 keV & 500 mA

- Measuring the (absolute) bound-electron g factor in the strongest fields of nuclei with $Z \geq 82$



Thank you for your attention!

– Questions?

ERC AdG 832848 - FunI

DFG SFB 1225

And thanks to…

…the **ALPHATRAP** Team

Matthew Bohman, Luca Geißler, Jonathan Grieshaber, Fabian Heiße, Philipp Justus, Sven Sturm, and Klaus Blaum

Former members:
Charlotte M. König, Jonathan Morgner (**Sn**),
Tim Sailer (**Ne**), Bingsheng Tu

…the **COALA** Team

Emily Burbach, Kristian König,
and Wilfried Nörtershäuser
& Others

…and our **theory colleagues**

Natalia S. Oreshkina, Bastian Sikora, Vladimir Yerokhin, Zoltan Harman, and Christoph H. Keitel

Acknowledgements

This work was supported by
the Max Planck Society,
the IMPRS-QD, the IMPRS-PTFS,
the DFG (SFB 1225 - ISOQUANT) and
the EU (ERC Grant No. 832848 FunI).