Precision Tests of Fundamental Interactions and Their Symmetries using Exotic Ions in Penning Traps

- **Basics of Penning-trap spectroscopy**
- **Atomic and nuclear mass measurements**
- **Precision *g*-factor measurements**

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Shanghai, Nov 23nd, 2023

European Research Council
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Atomic/nuclear spectroscopy …

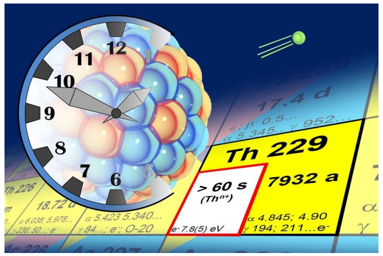
… probes fundamental physics!

How heavy are the building blocks of matter?

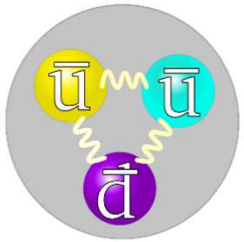
What is the mass of a neutrino?

Why is there more matter than anti-matter?

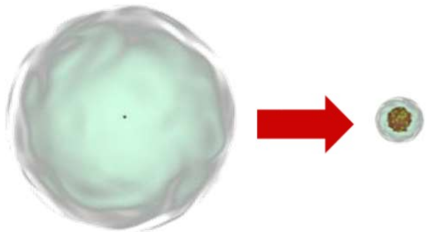
Does QED fail in the strong field regime?



- radionuclides

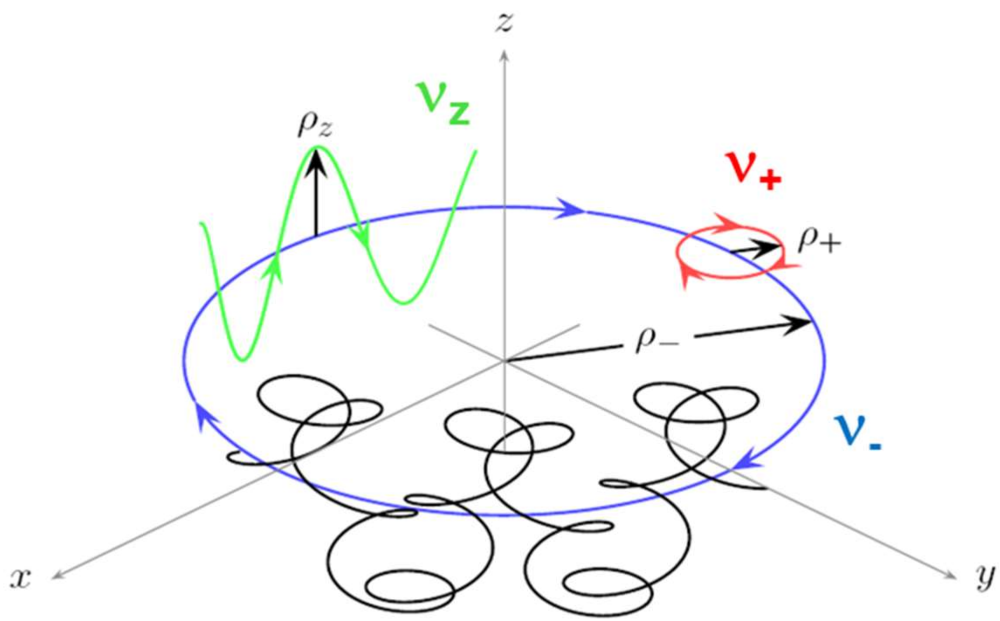


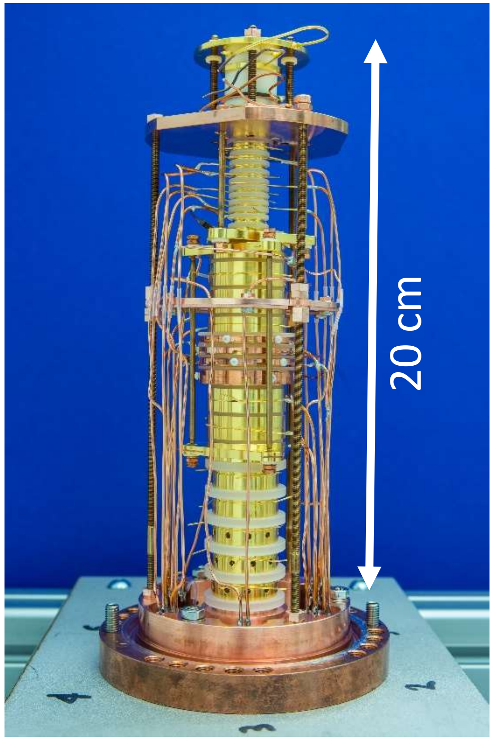
- antimatter



- highly charged ions

Storage of ions in a Penning trap





The free cyclotron frequency is inverse proportional to the mass of the ion!

$$\nu_c = qB / (2\pi m_{ion})$$

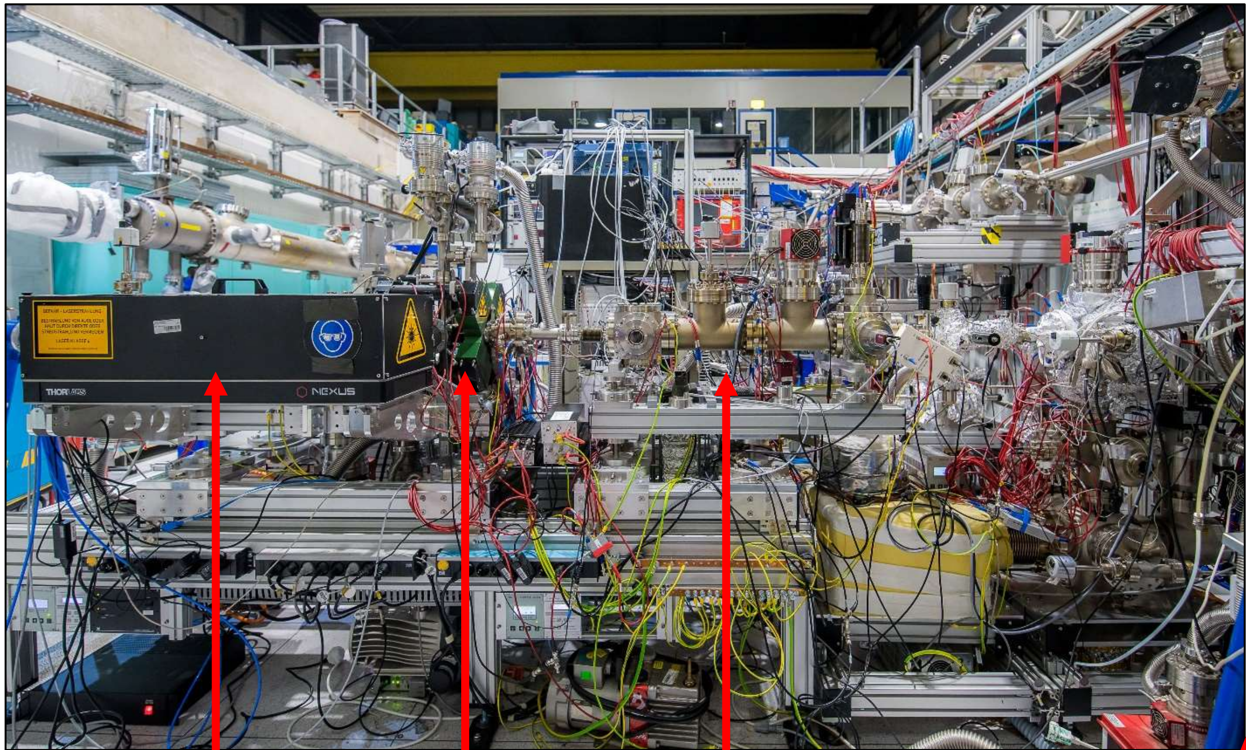
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

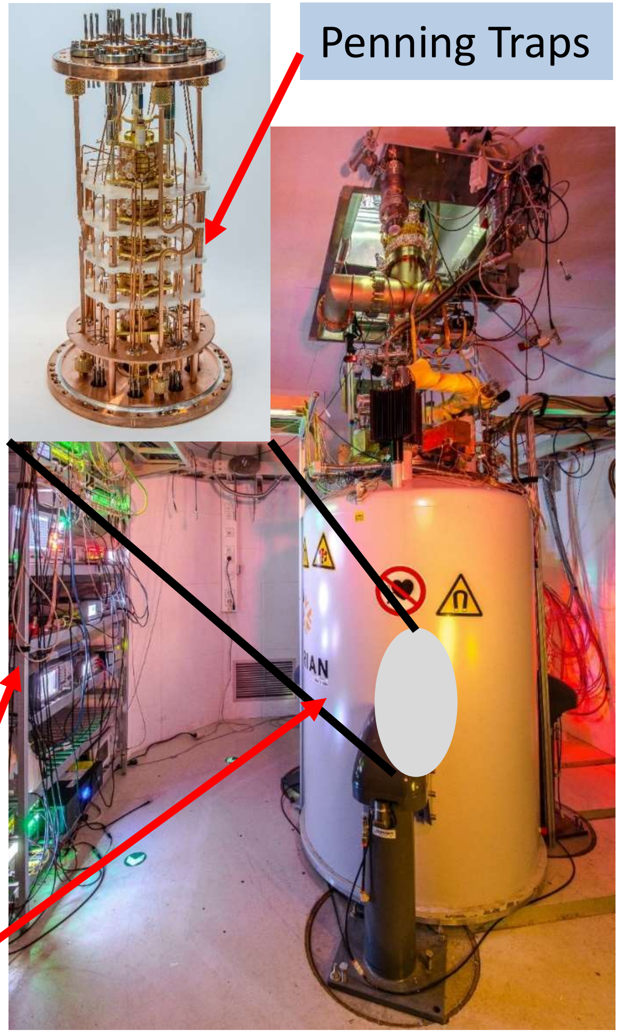
➢ Non-destructive FT-ICR detection technique

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. **58** (1986) 233

PENTATRAP – A Penning-trap setup at MPIK

A balance for highly charged ions.





Penning Traps

Laser Ion Source

EBIT

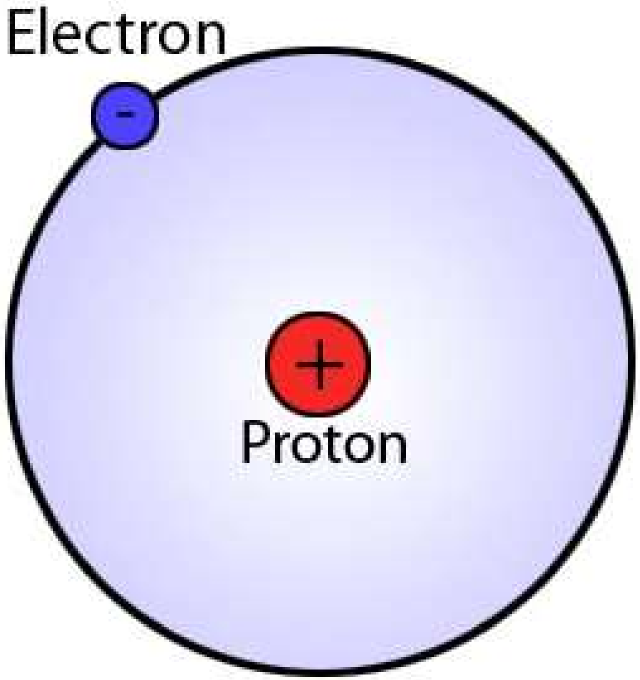
Transfer Beamline

Electronics

Superconducting Magnet

Results I

The masses of the building bocks of matter

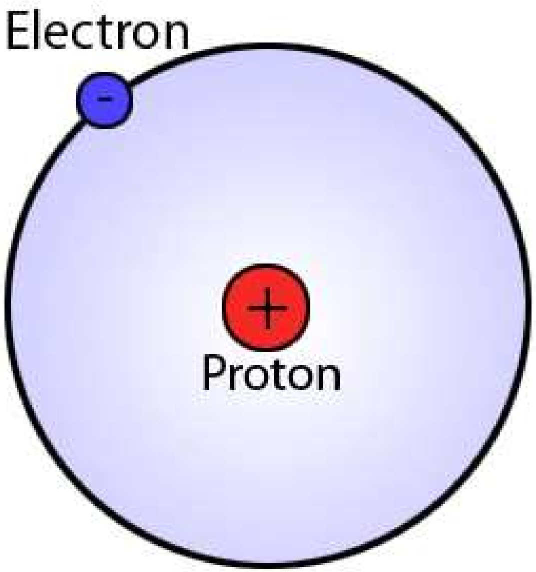


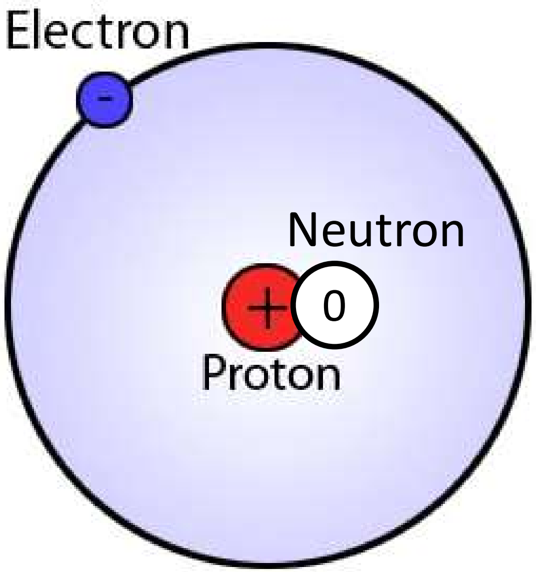
LIONTRAP: MPIK, Uni Mainz, GSI

The building blocks of matter

The atomic masses of the proton and electron and neutron. ☺

Hydrogen





Deuterium

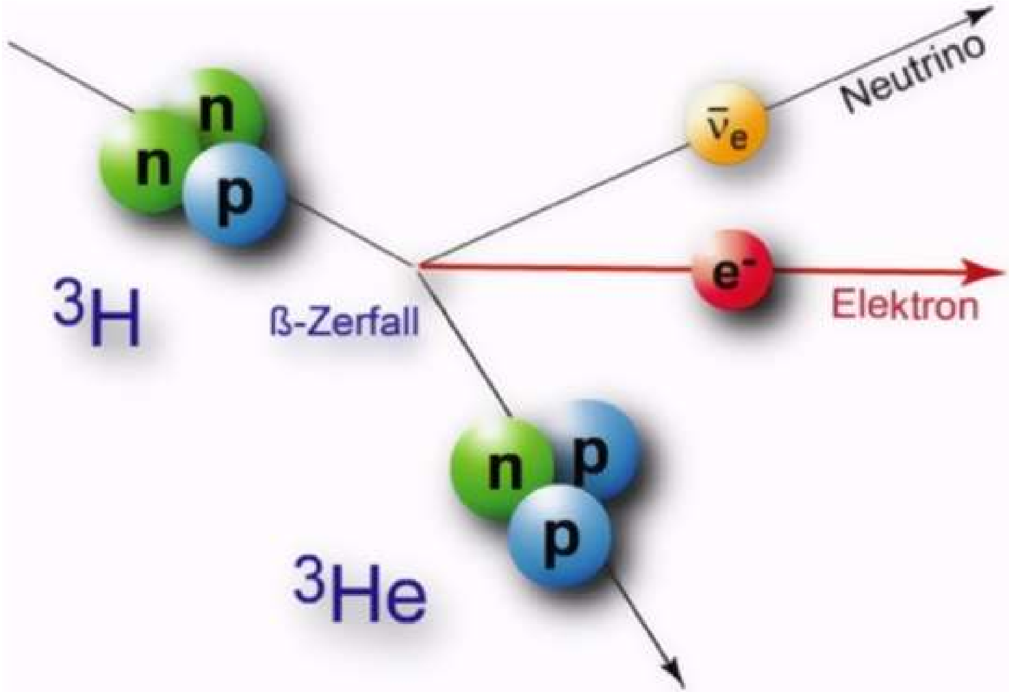
Electron: previous best value improved by a factor of 13	Proton: previous best value improved by a factor of 3	Deuteron: previous best value improved by a factor of ~3
m_e = 0.000 548 579 909 067(17) u	m_p = 1.007 276 466 583 (33) u	m_d = 2.013 553 212 535 (17) u
Nature **506** (2014) 467	Phys. Rev. Lett. **119** (2017) 033001	Nature **585** (2020) 43

Results II

Nuclear masses for neutrino physics

***Q*-values:**

$^{3}T \rightarrow {}^{3}He$
$^{163}Ho \rightarrow {}^{163}Dy$
$^{187}Re \rightarrow {}^{187}Os$



β^- -decay of ^{187}Re

$$R = \frac{\nu_c(^{187}\mathrm{Os}^{29+})}{\nu_c(^{187}\mathrm{Re}^{29+})}$$

$$Q = M(^{187}\mathrm{Re})\text{-}M(^{187}\mathrm{Os}) = M(^{187}\mathrm{Re}^{29+}) - M(^{187}\mathrm{Os}^{29+}) + \Delta B = M(^{187}\mathrm{Os}^{29+}) \cdot [R-1] + \Delta B$$

Measurement principle at PENTATRAP

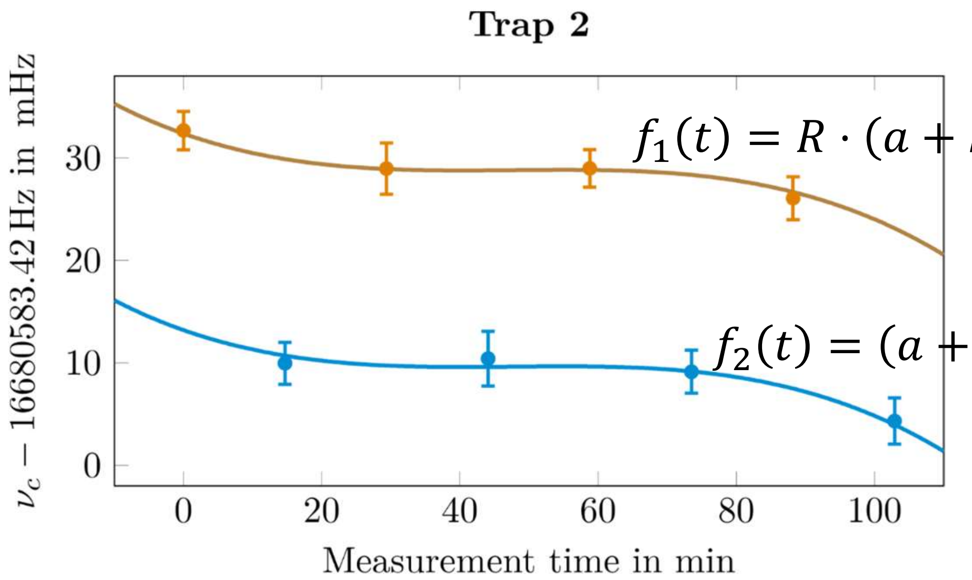
Mass Ratio determination – Polynomial Method

$$\omega_c = \frac{q}{m} \cdot B$$

Magnetic field not known!

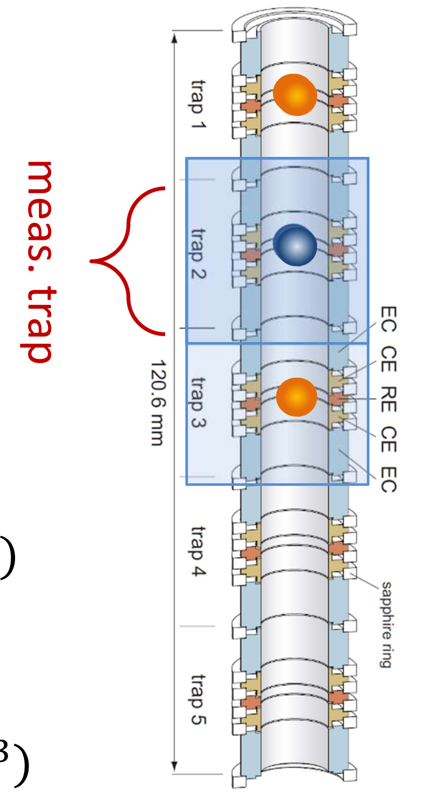
Second ion:

$$R = \frac{\omega_1}{\omega_2} = \frac{q_1 \cdot m_2}{q_2 \cdot m_1}$$



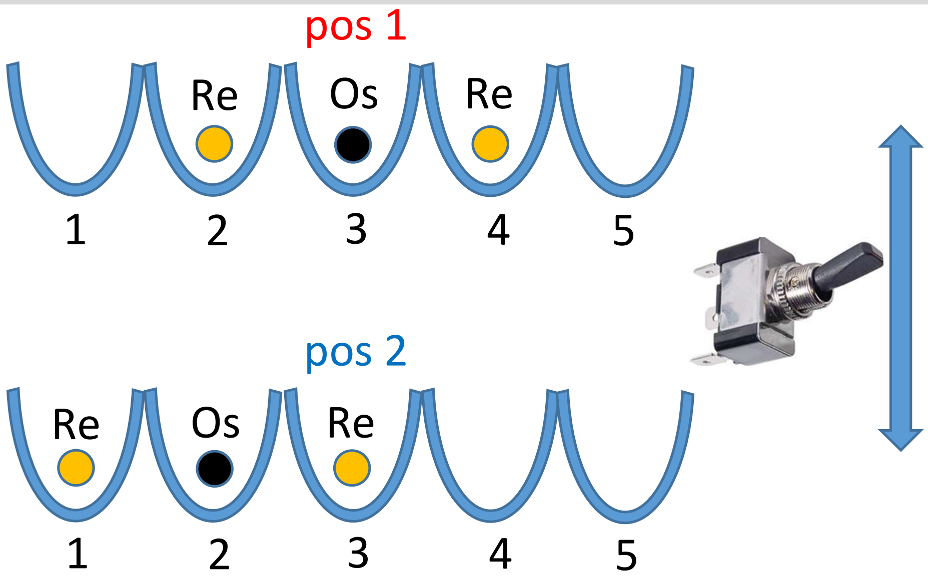
$$f_1(t) = R \cdot (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$

$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



A. Rischka *et al*., Phys. Rev. Lett. **124** (2020) 113001

Q-value of ^{187}Re-^{187}Os for neutrino physics



- Change position every 30 min
- Measurement of ν_+, ν_z, ν_-
- Phase detection method
- Storage time of days

P. Filianin *et al.*, Phys. Rev. Lett. **127** (2021) 072502

relative nuclear mass precision achieved: $6 \cdot 10^{-12}$

BUT

For Re^{29+} (Z = 75) vs. Os^{29+} (Z = 76) we measure two ratios with a 50/50 probability:

R_1 = 1.000000013886(15)

R_2 = 1.000000015024(12)

Weighing of different electron config.

Ground-state configuration of Re^{29+} and Os^{30+}: $[_{36}Kr]\ 4d^{10}$

Metastable state $[_{36}Kr]\ 4d^9\ 4f^1$ with $E_{exc} \approx 200$ eV in Re^{29+}

Similar state in Os^{30+} expected!

Re^{29+}

metastable state

$B_{PENTATRAP}$ = 202.2(17) eV

B_{Harman} = 202.2(5) eV

$B_{Indelicato}$ = 202.1 (27) eV

$B_{Haverkort}$ = 202.8(4) eV

ground state

Os^{30+}

metastable state

$B_{PENTATRAP}$ = 207(3) eV

$B_{Haverkort}$ = 209(2) eV

$B_{Indelicato}$ = 207(3) eV

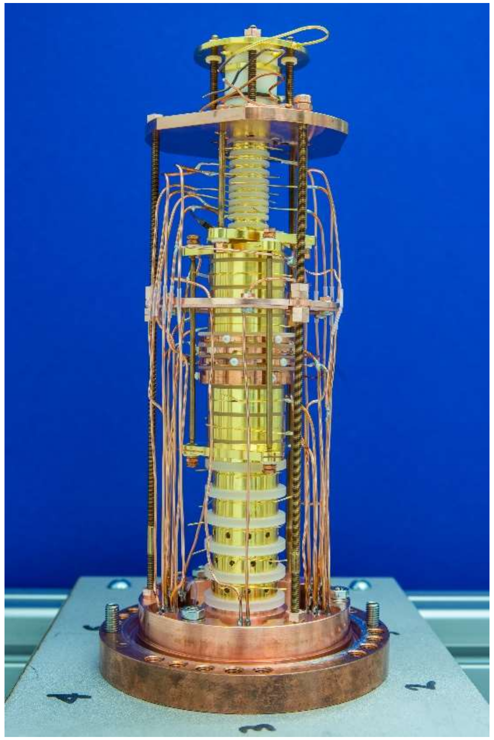
ground state

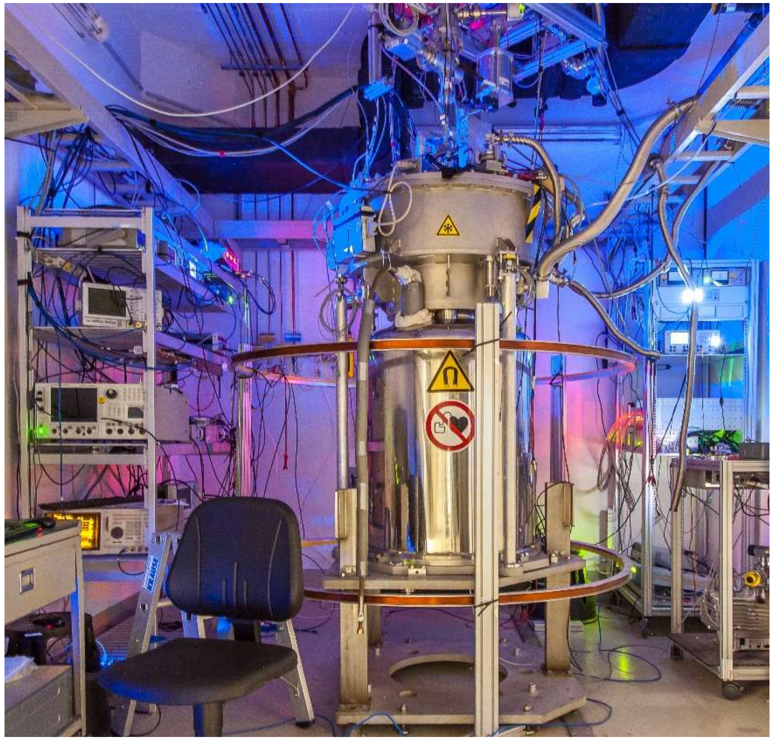
R. Schüssler *et al.*, Nature **581** (2020) 42

Possible application: search for suitable clock transitions

Results III

Tests of fundamental interactions and their symmetries





ALPHATRAP, BASE, PENTATRAP: MPIK, PTB, RIKEN

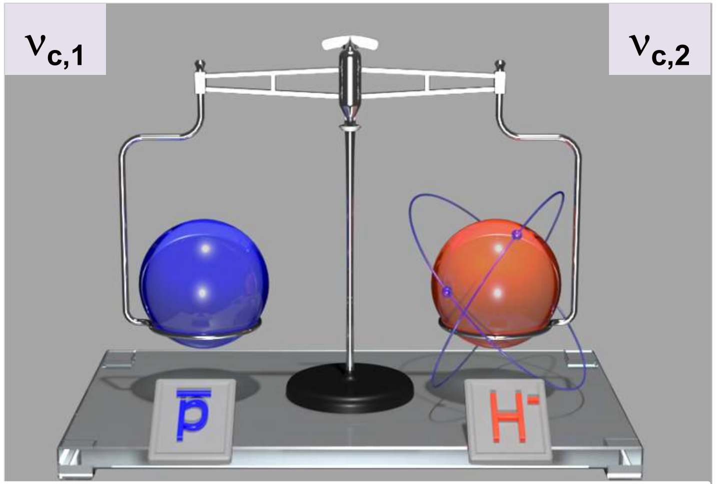
European Research Council
Established by the European Commission

Comparison of the proton and antiproton

Compare charge-to-mass ratios *R* of p and $\bar{\text{p}}$:

$(q/m)_{\bar{p}} / (q/m)_{p}$ **= -1.000 000 000 003 (16)**

M.J. Borchert *et al.*, Nature **601** (2022) 53

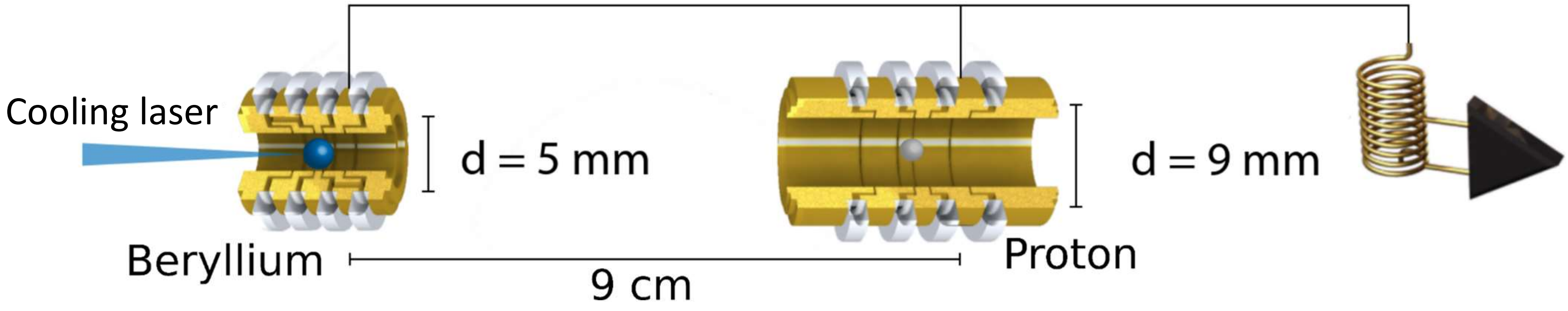


It is not that easy!

$$m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{\mathrm{pol,H^-}} B_0^2}{m_p} - \frac{E_\mathrm{b}}{m_p} - \frac{E_\mathrm{a}}{m_p}\right)$$

Most stringent test of CPT symmetry in the baryon sector!

Sympathetic laser cooling of a proton



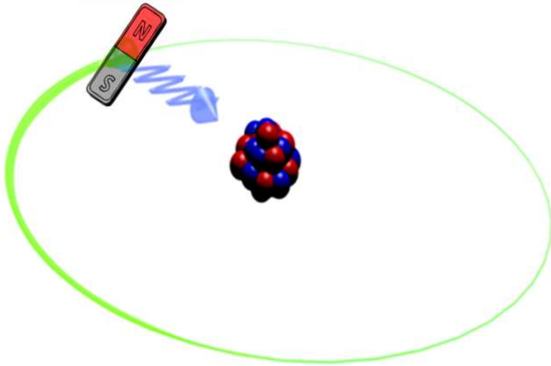
M.Bohman *et al.*, Nature **596** (2021) 514

B. Tu *et al.*, AQT **210009** (2021) 1

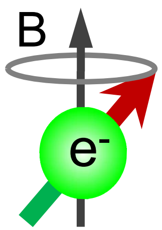
Proton axial temperature of ~ 100 mK demonstrated!

The g-factor of the bound electron

Study one electron bound to the nucleus, e.g. $^{12}C^{5+}$ (highly charged ions)



g-factor: measure for the magnetic strength of the bound electron

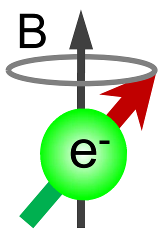


Electron acts like a spinning top in the magnetic field with frequency ω_L

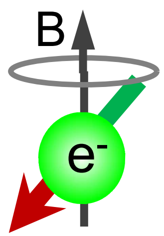
$$\omega_L = \frac{g}{2}\frac{e}{m_e}B$$

Electron can be in spin-up or spin-down state with transition frequency ω_L

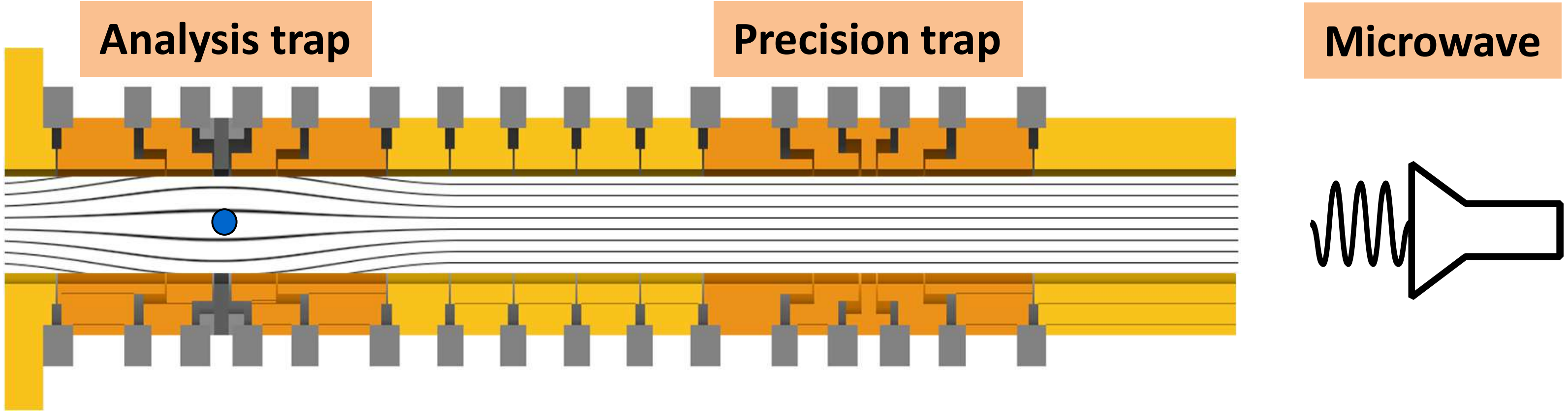
spin-up

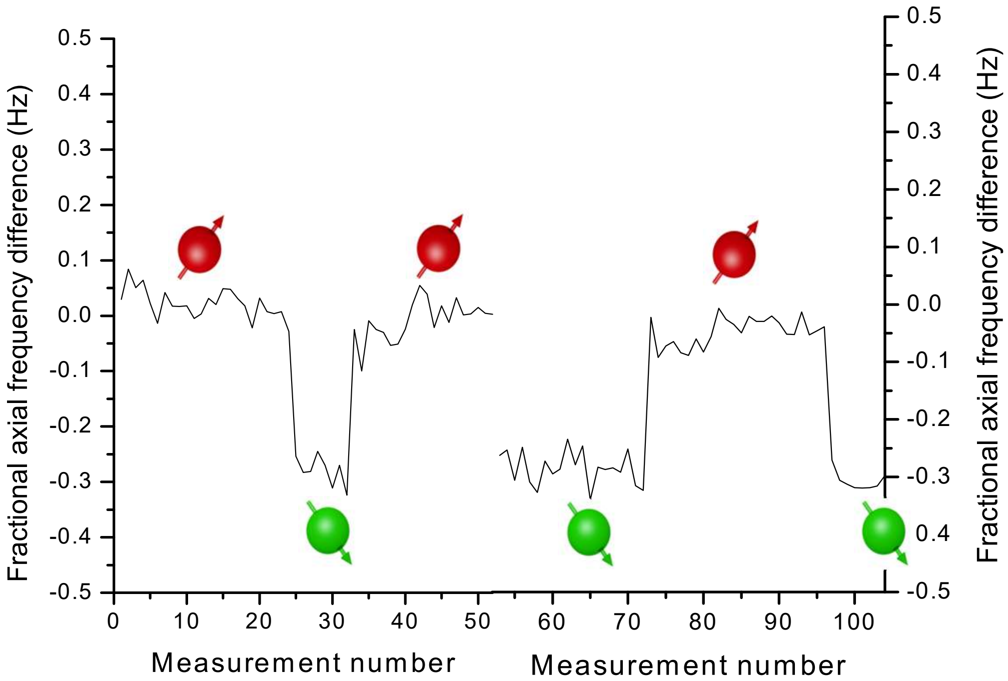


spin-down



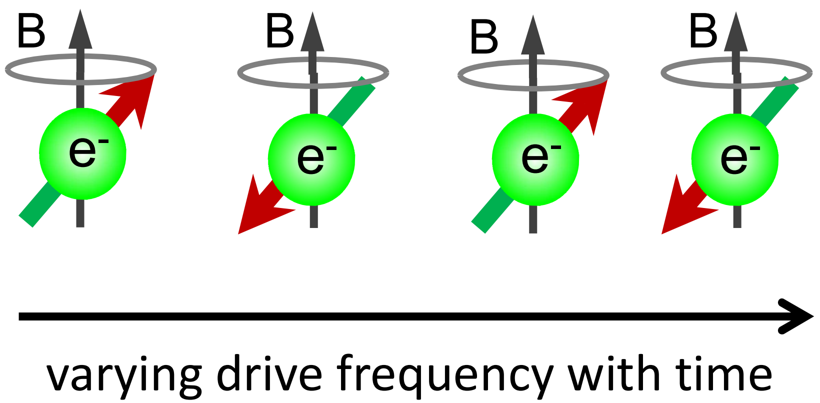
g-factor measurement process

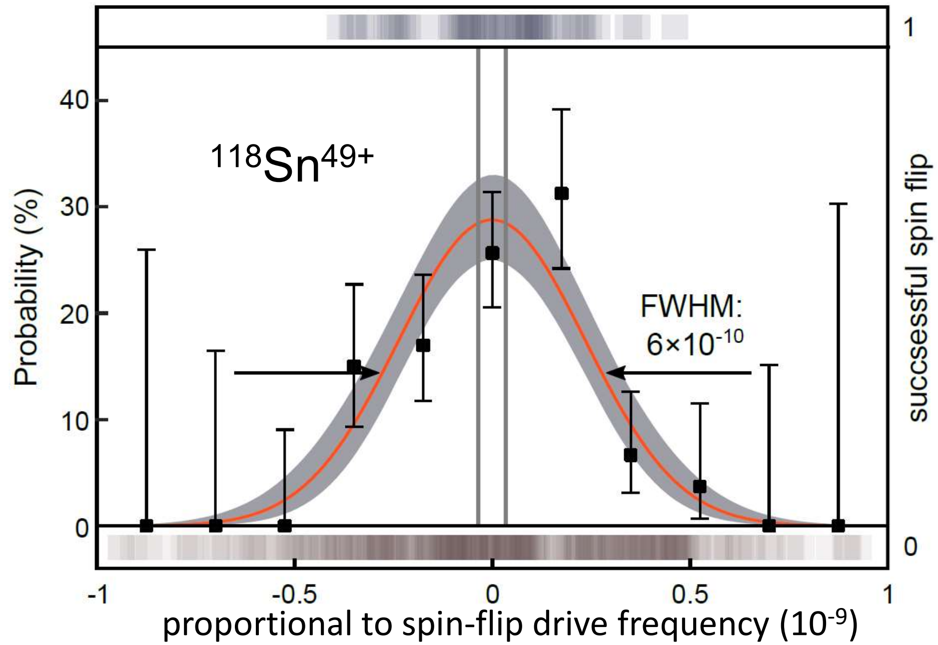




<u>Measurement cycle</u>	time
▪ Detection of spin-state	2-3min
▪ Transport	20s
▪ ν_c measurement and microwave irradiation	10min
▪ Transport	20s
▪ Detection of spin-state	

Test of QED in strong fields





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

g_{exp} = 1.998 767 276 93 (16)
g_{theo} = 1.998 767 277 11 (12)

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

g_{exp} = 1.910 562 058 (1)
g_{theo} = 1.910 561 821 (299)

Stringent test of bound-state QED in strong fields!

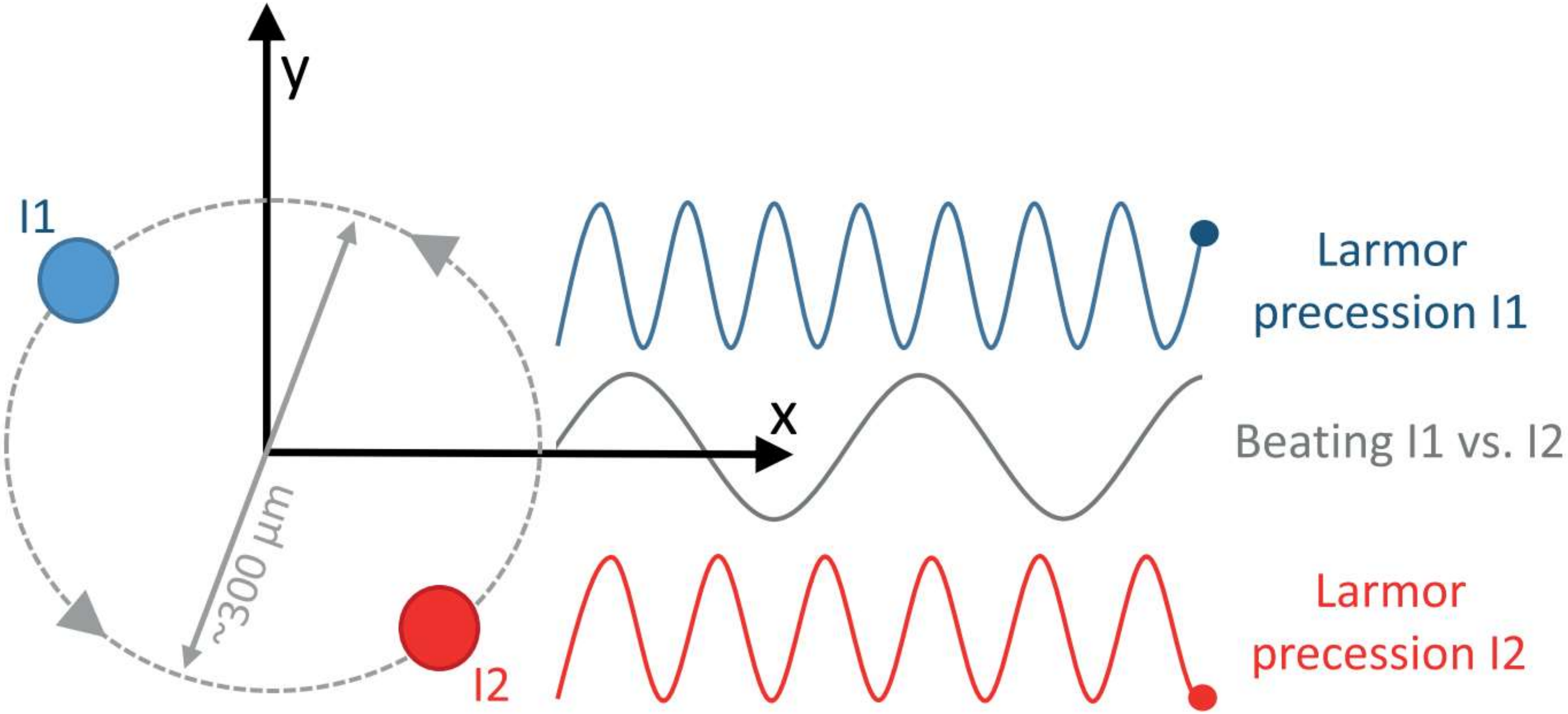
Theory colleagues: Harman, Keitel, Oreshkina, Yerokhin

T. Sailer *et al.*, Nature **606**, 479 (2022)
F. Heiße *et al.*, Phys. Rev. Lett., **in print** (2023)
J. Morgner *et al.*, Nature **622**, 53 (2023)

Bound *g*-factor difference in coupled ions

Delta-*g* measurement in $^{20,22}Ne^{9+}$: how to get ν_L

Probability of common spin behavior modulated by beat frequency!



Relative precision of $5 \cdot 10^{-13}$ achieved, most stringent BS-QED test!

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

Summary

Precision Penning-trap spectroscopy has reached an amazing precision even on exotic systems and has opened up many new fields of research!

Max Planck Society ***IMPRS-PTFS*** ***IMPRS-QD*** ***ERC AdG 832848 - FunI*** ***DFG***