MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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

- **Basics of Penning-trap spectroscopy**
- **Masses of the building blocks of matter**
- **Atomic binding and excitation energies**
- **Tests of fundamental symmetries**

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

ICOLS, June 26th, 2023

TC FS

European Research Council
Established by the European Commission

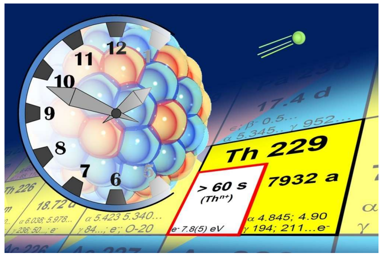
Atomic/nuclear spectroscopy …

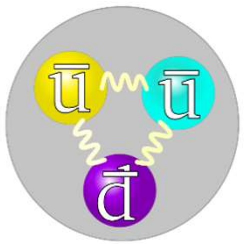
… probes fundamental physics!

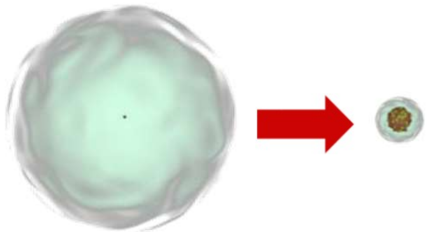
How heavy are the building blocks of matter?

Why is there more matter than anti-matter?

Does QED fail in the strong field regime?

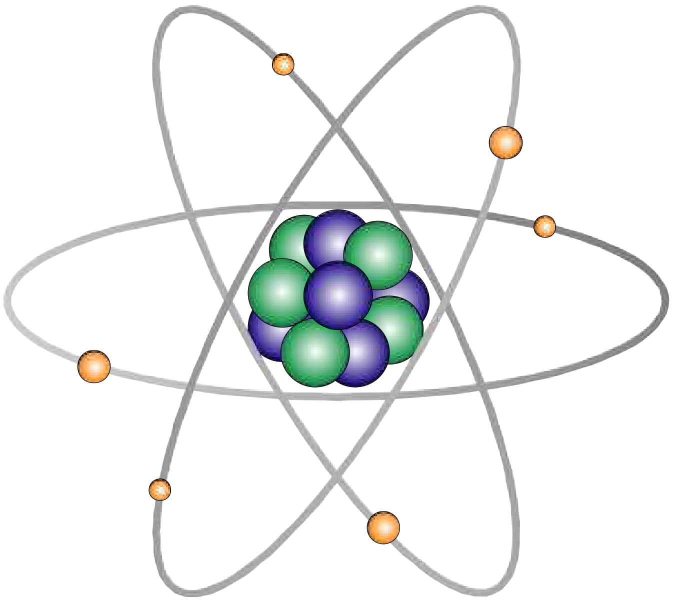


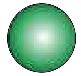
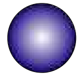




- ➢ radionuclides
- ➢ antimatter
- ➢ highly charged ions

The mass of an atom



$= N \cdot$  $+ Z \cdot$  $+ Z \cdot$ 

– binding energy

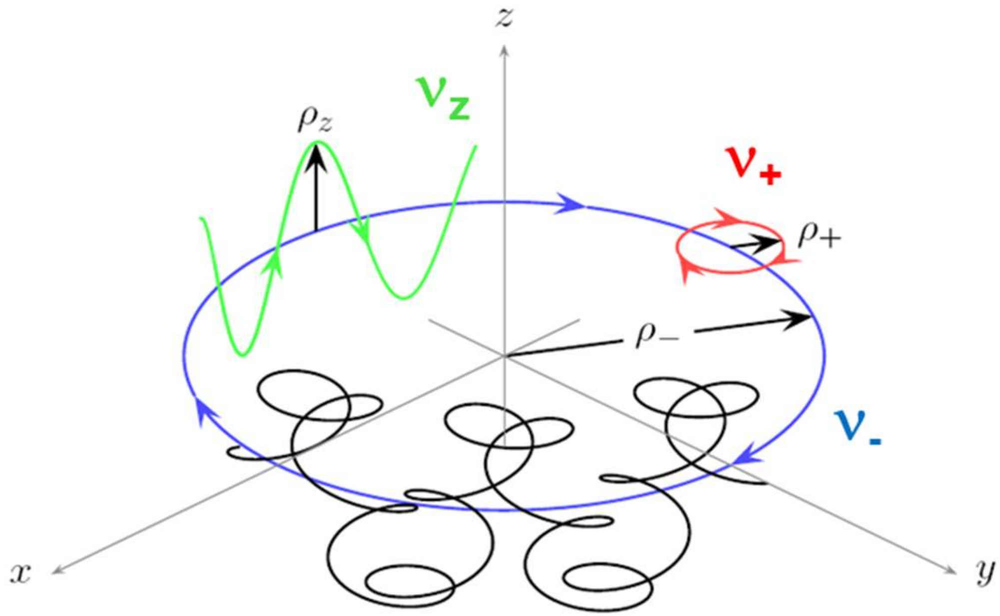
Einstein $E = mc^2$

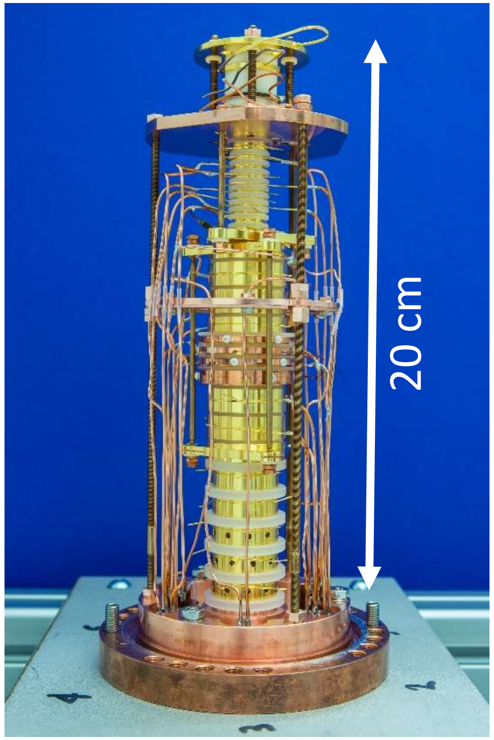
$$m_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} – 10^{-8}$

Storage of ions in a Penning trap





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

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

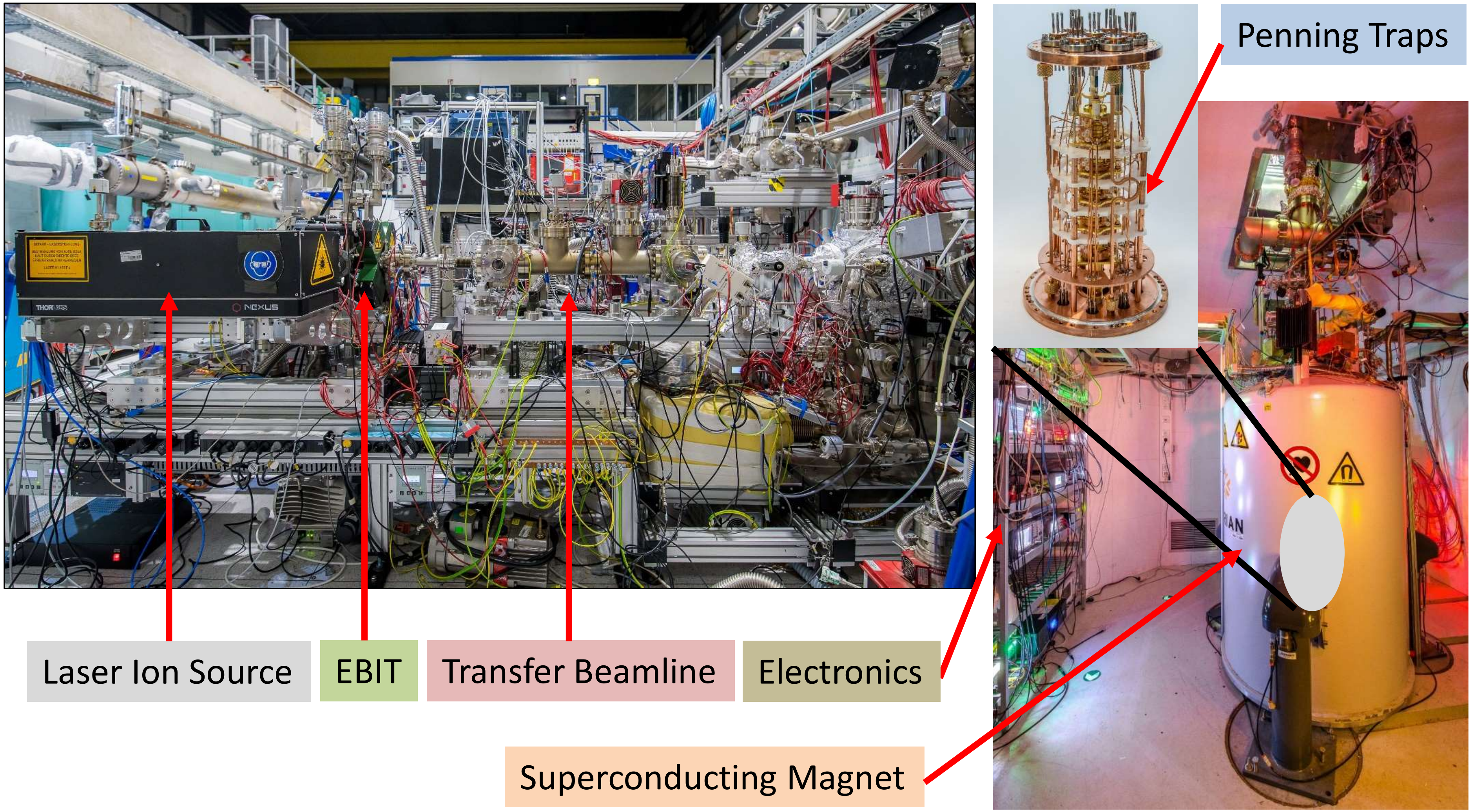
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

➢ Non-destructive FT-ICR detection technique

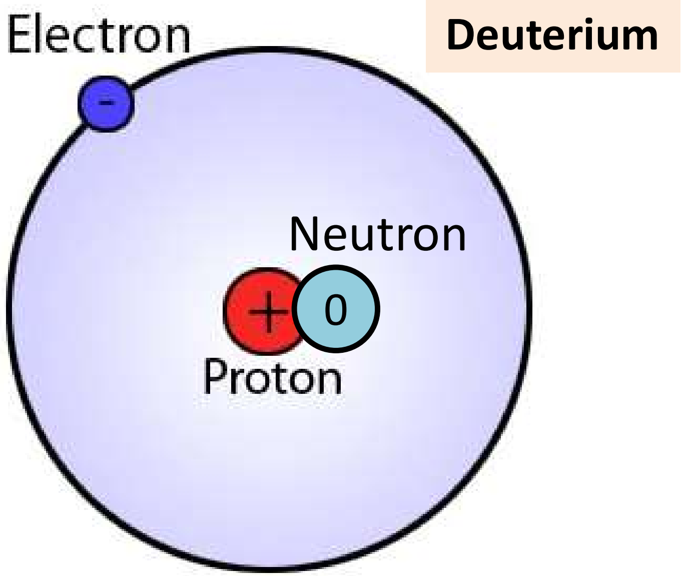
L.S. Brown, G. Gabrielse, Rev. Mod. Phys. **58** (1986) 233

PENTATRAP – A Penning-trap setup at MPIK

A balance for highly charged ions.



The atomic mass of the deuteron and HD$^+$



$$m_\mathrm{d} = \frac{1}{6}\frac{\nu_\mathrm{c}(^{12}\mathrm{C}^{6+})}{\nu_\mathrm{c}(\mathrm{d})} m(^{12}\mathrm{C}^{6+})$$

A factor of ~3 improved value and 6.6 sigma deviation!

$$m_\mathrm{d} = 2.013553212535(11)_\mathrm{stat}(13)_\mathrm{sys}(17)_\mathrm{tot}\ \mathrm{AMU} \qquad \frac{\delta m_\mathrm{d}}{m_\mathrm{d}} = 8.5\times 10^{-12}$$

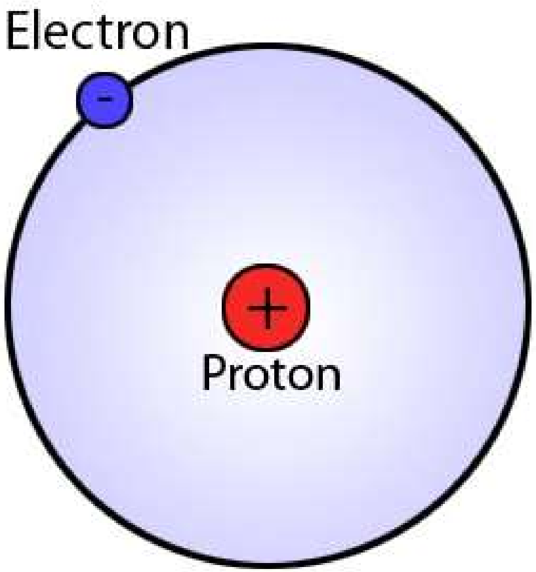
→ Provides access to the mass of the neutron

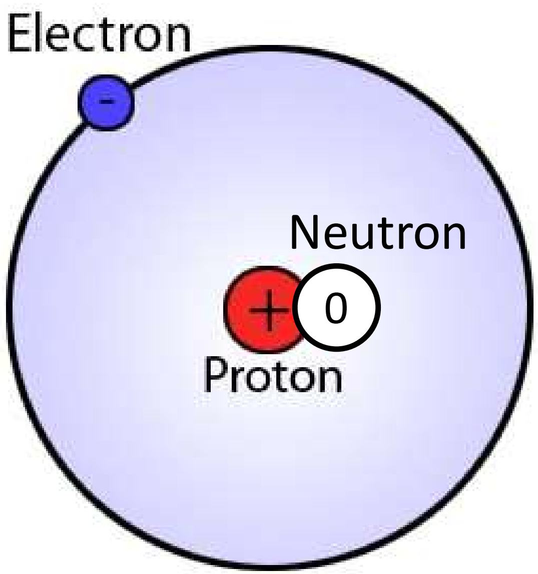
S. Rau *et al.*, Nature **585** (2020) 43

The building blocks of matter

The atomic mass of the proton and electron   and neutron ☺

Hydrogen





Deuterium

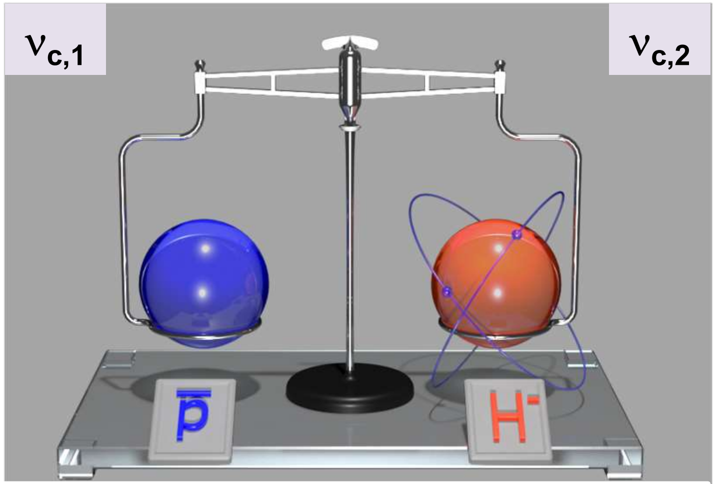
Electron: previous best value improved by a factor of 13	Proton: previous best value improved by a factor of 3	deuteron: previous best value improved by a factor of ~3
m_e = 0.000 548 579 909 067(17) u	m_p = 1.007 276 466 583 (33) u	m_d = 2.013 553 212 535 (17) u
Nature **506** (2014) 467	Phys. Rev.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

Comparison of the proton and antiproton

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

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

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

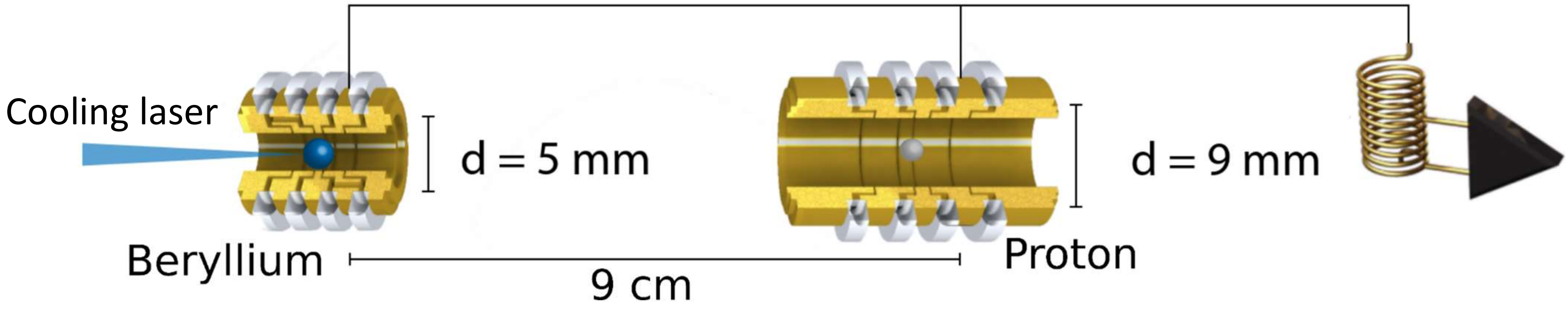


It is not that easy!

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

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!

Measurement principle at PENTATRAP

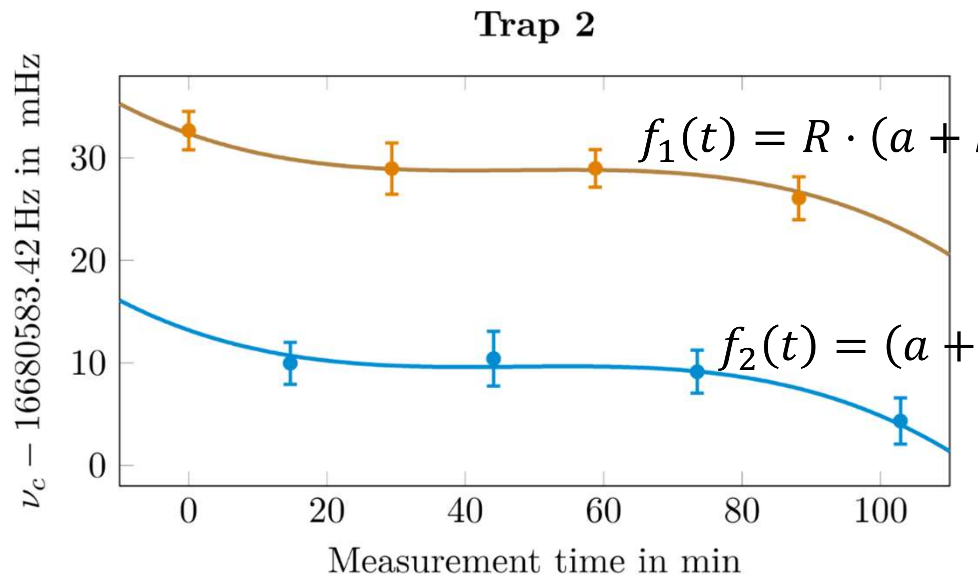
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

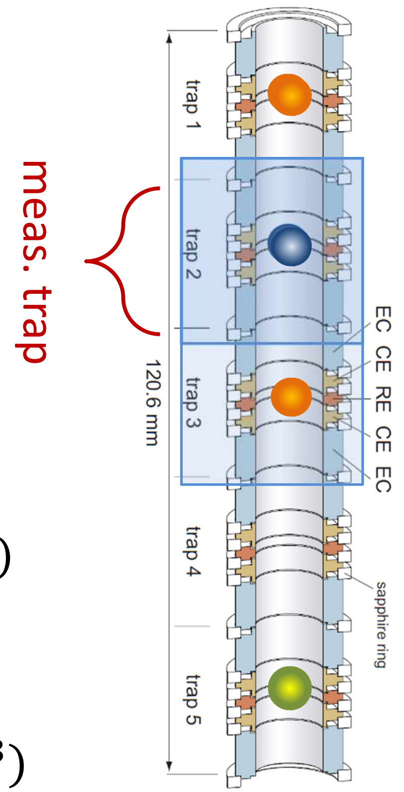
Second ion:

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



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

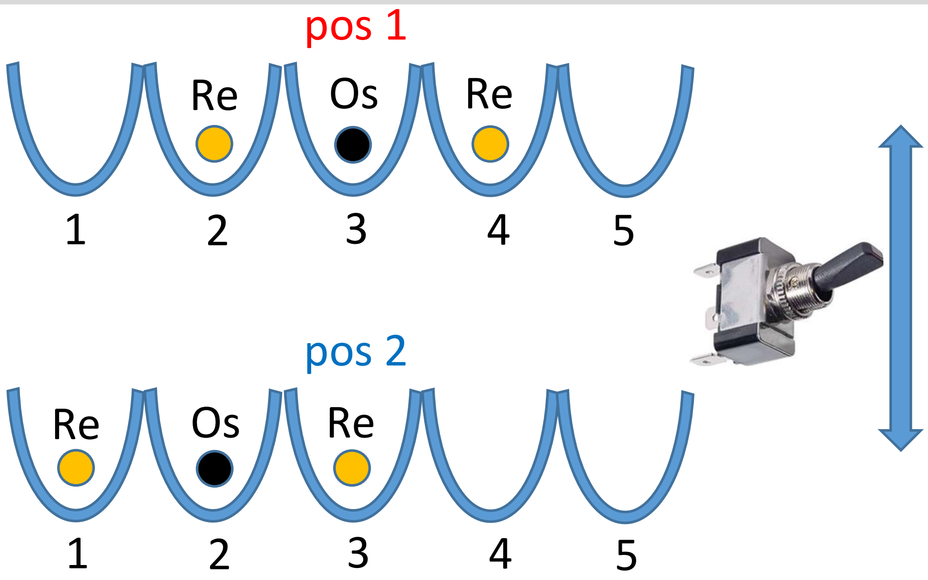
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



Future: Monitoring trap

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

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

B_{Harman} = 202.2(5) eV

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

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

ground state

Os^{30+}

metastable state

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

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

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

ground state

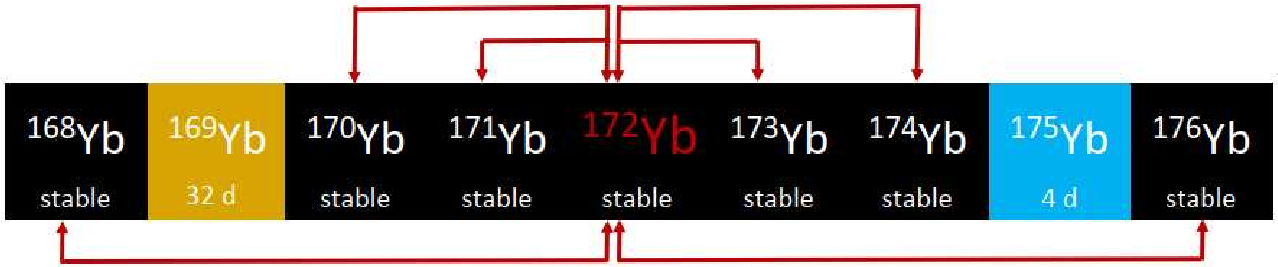
R. Schüssler *et al.*, Nature **581** (2020) 42

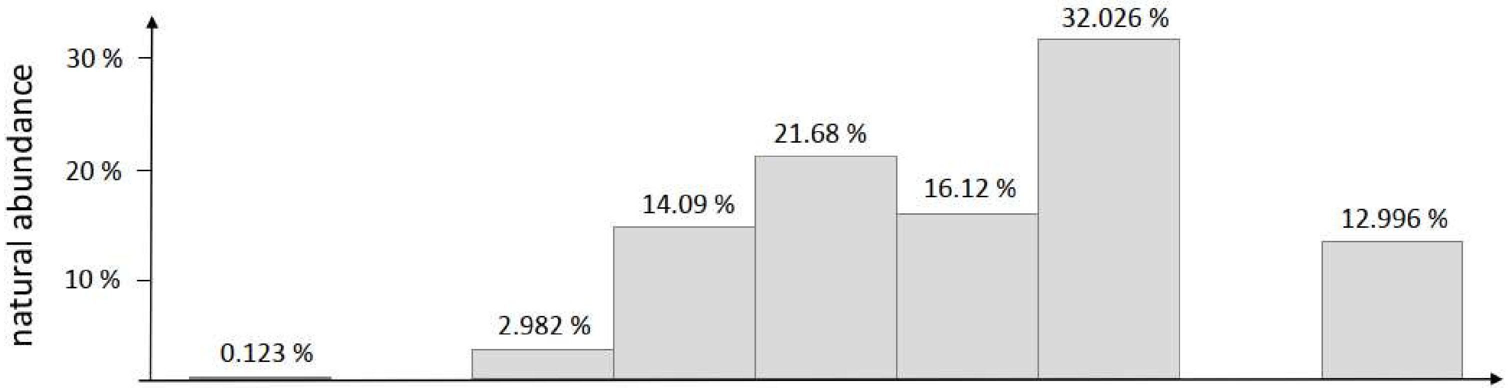
Possible application: search for suitable clock transitions

Yb mass-ratio measurements

Motivation: 5th force search using King-plot analysis in Ca, Sr, Yb

Mass-ratio uncertainties of 10^{-11} and below required!

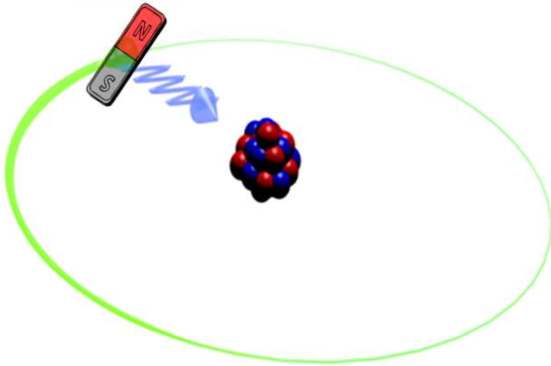




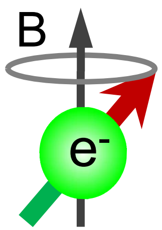
All even-even mass ratios measured. ☺
Relative mass uncertainty: ~$4 \cdot 10^{-12}$, improvement factor: typically >50

The *g*-factor of the bound electron

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



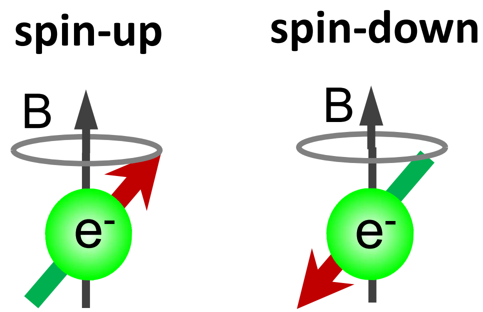
g-factor: measure for the magnetic strength of the bound electron



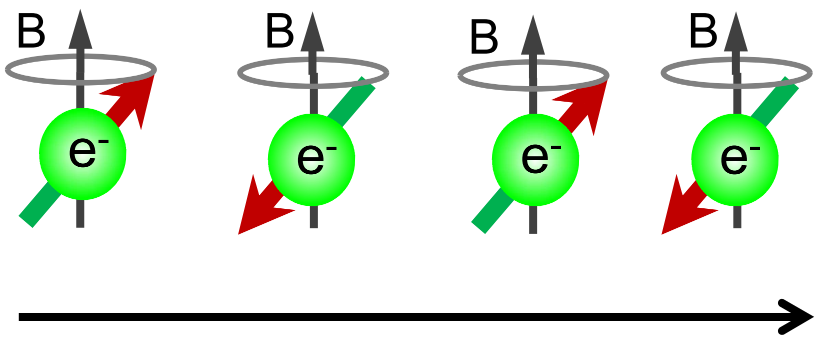
Electron acts like a spinning top in the magnetic field with frequency ω_L

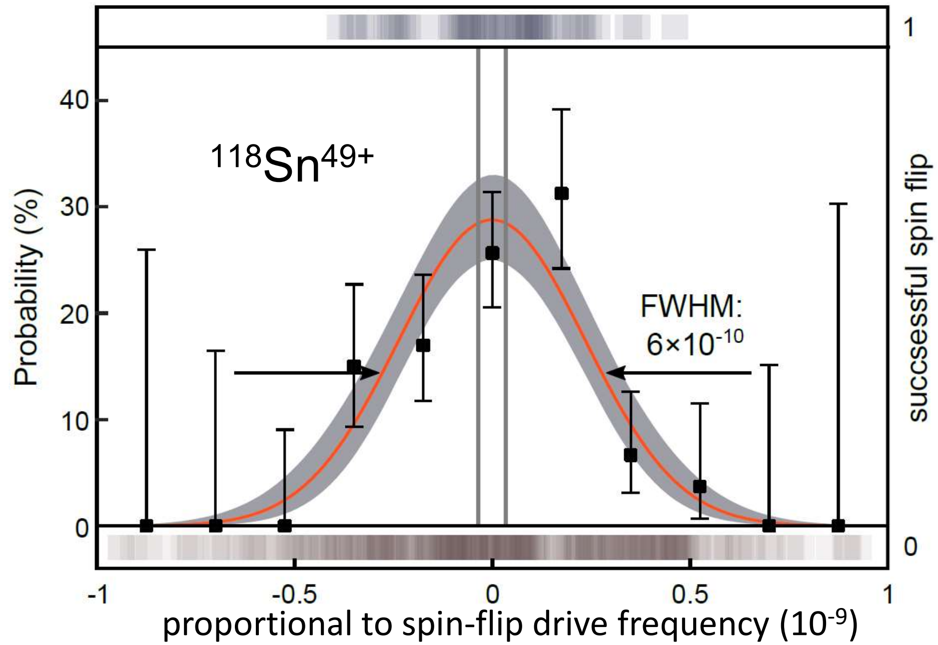
$$\omega_L = \frac{g}{2}\frac{e}{m_e}B$$

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



Test of QED in strong fields





$^{20}Ne^{9+}$	$^{118}Sn^{49+}$
g_{exp} = 1.998 767 276 93 (16)	g_{exp} = 1.910 562 058 (1)
g_{theo} = 1.998 767 277 11 (12)	g_{theo} = 1.910 561 821 (299)

Most stringent test of bound-state QED in strong fields!

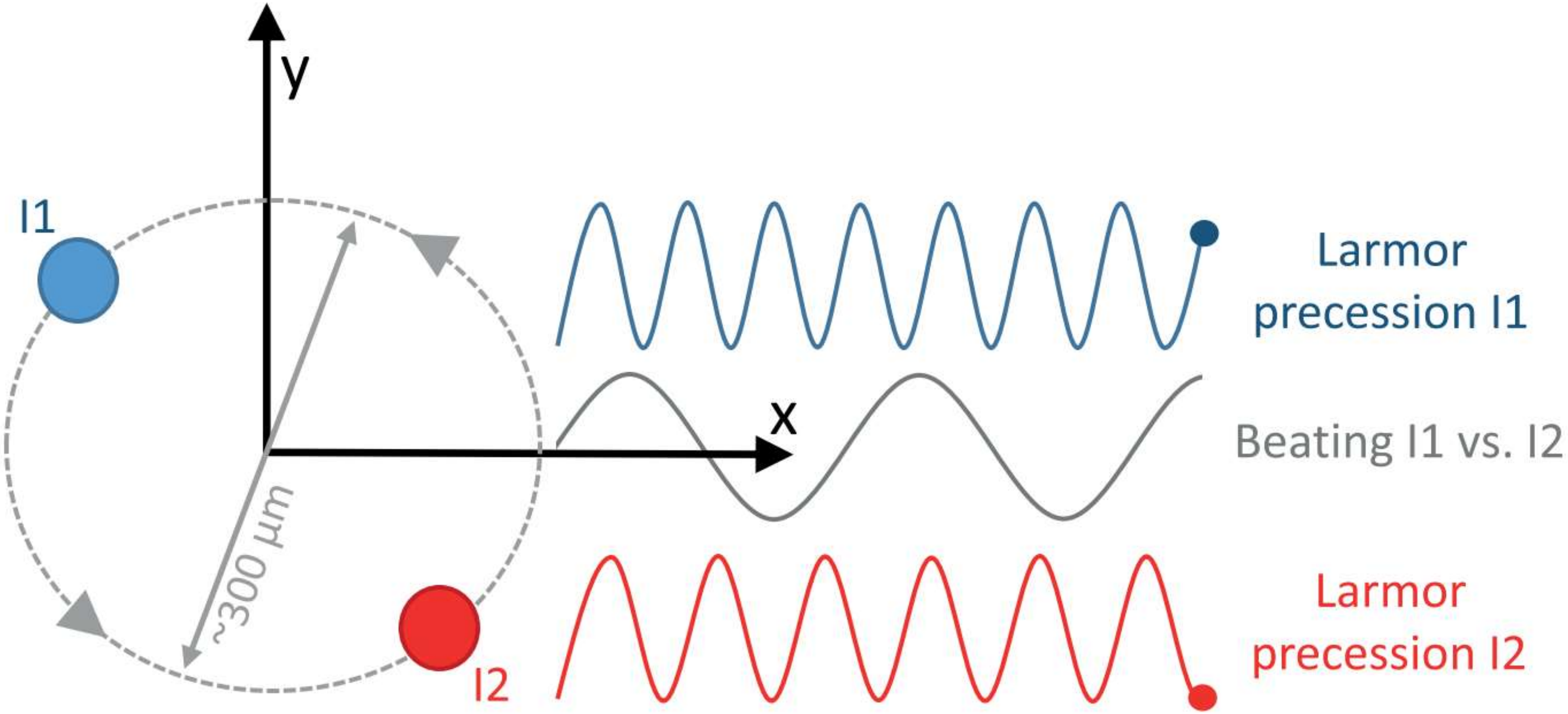
Theory colleagues: Harman, Keitel, Oreshkina, Yerokhin

T. Sailer *et al.*, Nature **606**, 479 (2022)
F. Heiße *et al.*, Phys. Rev. Lett. **submitted** (2023)
J. Morgner *et al.*, Nature **accepted** (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 mass spectrometry and g-factor measurements have 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***