The $^{40}Ar^{13+}$ g-factor and fine structure splitting measurements of the ALPHATRAP experiment

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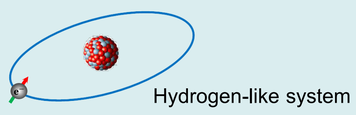
The *g*-factor of highly charged ions

- The *g*-factor of the bound electron is altered by bound-state quantum electrodynamic (BS-QED) effects

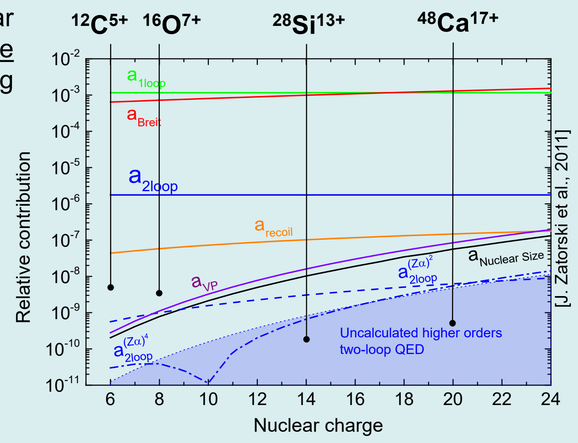
$$g = 2(1 + a_{Breit} + a_{1loop} + a_{NuclearSize} + a_{2loop} + a_{recoil} + \ldots)$$

- BS-QED calculations can be tested with high-precision *g*-factor measurements of electrons bound in highly charged ions [1]
- BS-QED effects increase with the nuclear charge state. Therefore <u>few or single</u> electron systems are especially interesting (fieldstrengths up to ~10^{18} V/m)



Hydrogen-like system

High precision measurements of $^{12}C^{5+}$,$^{16}O^{7+}$, $^{28}Si^{13+}$ and up to $^{48}Ca^{17+}$ have been performed at the Mainz *g*-factor experiment [2-7]



g-factor: $\overrightarrow{\mu_s} = -g_s \mu_B \frac{\vec{s}}{\hbar}$

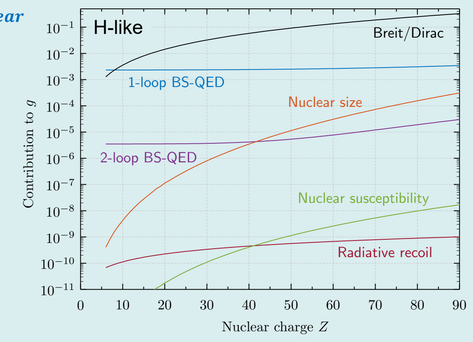
Relates the magnetic moment $\overrightarrow{\mu_s}$ to the spin $\vec{s}$

QED test and fundamental constants

ALPHATRAP @ MPIK - "pushing the limits"

- follow-up of the Mainz *g*-factor experiment
- **access to Heidelberg-EBIT**
  → extend *g*-factor experiments to heavy-Z systems by using **heavy highly charged ions up to $^{208}Pb^{81+}$**
- probe QED in the most extreme fields, access fundamental constants

$$g = 2 + \Delta g_{relat.} + \Delta g_{QED} + \Delta g_{nuclear}$$



However, at high *Z* nuclear effects increase and are poorely known. **Comparison of the absolute *g*-factor values is therefore unfavorable** since the error will most likely be dominated by the uncertainty of the nuclear structure parameters. Instead, one can compare specific weighted *g*-factor differences, where nuclear effects can be canceled by a weight parameter ξ [8].

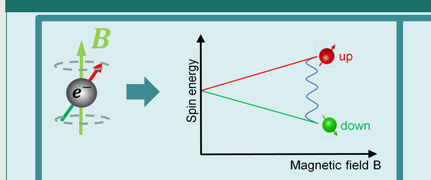
By measuring *g*-factor differences of **H-like** and **Li-like** ions, QED can be tested because nuclear contributions are highly suppressed.

$$\Delta g' = g_{(1s)^2(2s)^2} - \xi g_{1s}$$

By measuring *g*-factor differences of **H-like** and **B-like** ions will allow the determination of the **fine-structure constant α** to high precision [8].

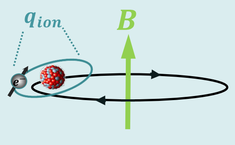
$$\Delta g' = g_{(1s)^2(2s)^2 2p_{1/2}} - \xi g_{1s}$$

Measurement principle



$$\nu_L = \frac{g}{4\pi}\frac{e}{m_e}B$$

Measure the Larmor frequency in a well-known magnetic field



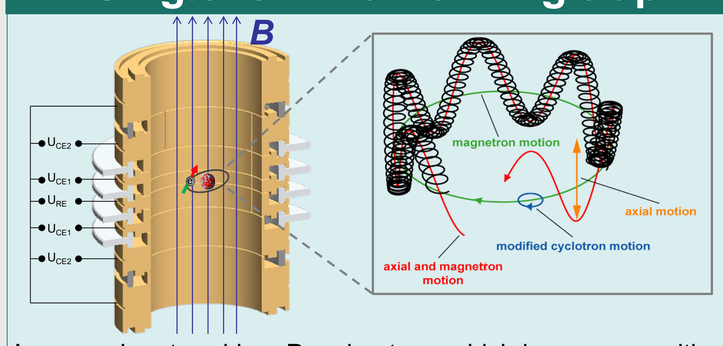
$$\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}}B$$

Measure the free cyclotron frequency to determine magnetic field

$$g = 2\frac{\nu_L}{\nu_c}\frac{q_{ion}}{e}\frac{m_e}{m_{ion}}$$

$\Gamma = \frac{\nu_L}{\nu_c}$ **has to be measured** — **Independent precision experiments [4,9]**

Single ion in a Penning trap

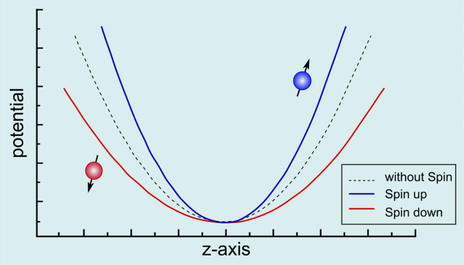


Ions can be stored in a Penning trap, which is a superposition of a strong, homogeneous magnetic field and an electrostatic quadrupolar potential. In the trap, the ions have three independent modes, where the eigenfrequencies obey the relation (invariance theorem[11]):

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

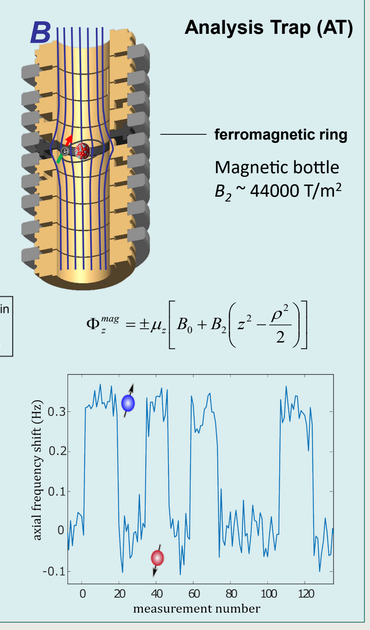
Continuous Stern-Gerlach effect

In order to detect the spin direction, a ferromagnetic ring in the analysis trap (AT) produces a magnetic field inhomogeneity (magnetic bottle), which couples the spin orientation to the axial frequency.



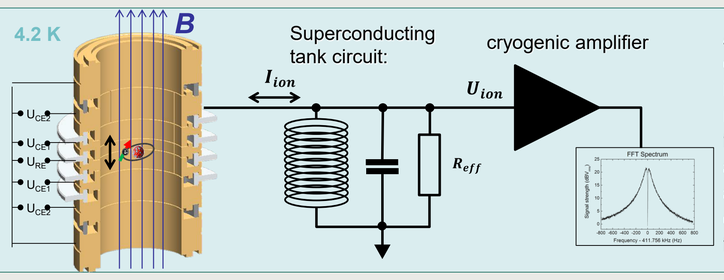
The axial potential and therefore also the axial frequency depend on the spin state of the electron. Thus, a spinflip can be observed via a change in the axial frequency given by

$$\Delta\nu_z \approx \frac{B_2 g \mu_B}{4\pi^2 m_{ion}\nu_z}$$



Frequency determination

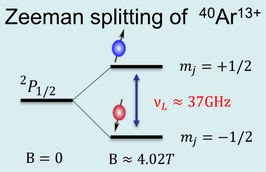
The ion oscillation induces tiny image currents (~fA) in the trap electrodes. A superconducting high impedance tank circuit converts these currents into a measurable voltage signal. This signal is then amplified by a cryogenic low noise amplifier and can be detected frequency- or phase-resolved [12].



At thermal equilibrium a "dip" in the Johnson noise density of the tank circuit appears exactly at the ion's oscillation frequency.

The *g*-factor of boronlike argon $^{40}Ar^{13+}$

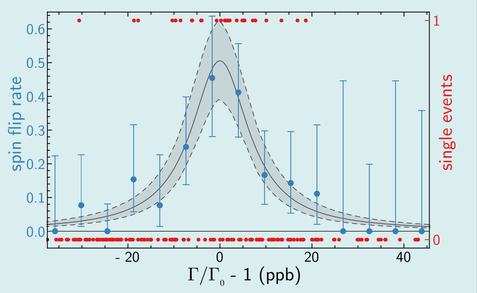
Zeeman splitting of $^{40}Ar^{13+}$

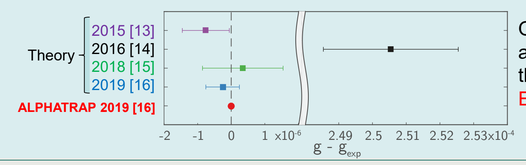


Probing the Zeeman transition multiple times for different Γ-ratios a resonance appears from which the *g*-factor is extracted by a Lorentzian most likelyhood fit.

$$g = 2\Gamma\frac{q_{ion}}{e}\frac{m_e}{m_{ion}} \qquad \Gamma = \frac{\nu_L}{\nu_c}$$

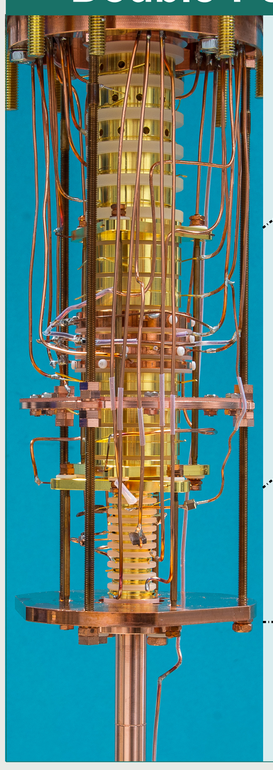
The exact Larmor frequency ν_L is determined by shining in microwaves around the supposed Larmor frequency. At ν_L the spinflip probability is maximized.





Our experimental result are in agreement with the current theory at 10^{-7} level.
Experiment precision at 10^{-9}

Double Penning trap setup



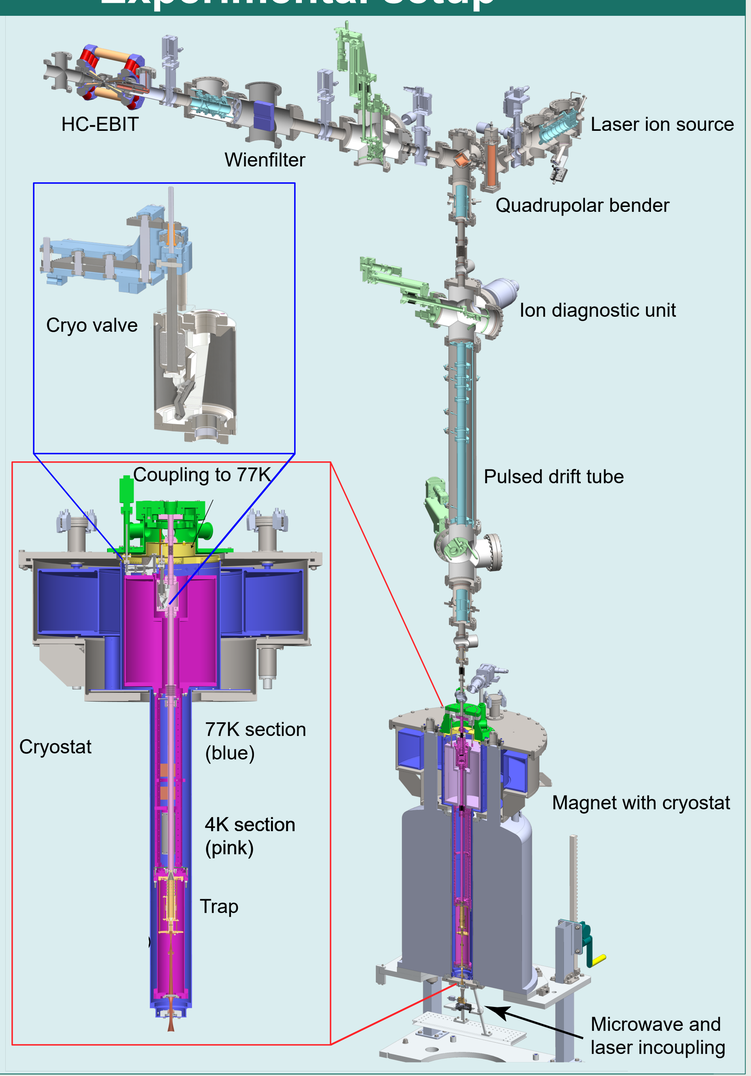
Capture electrodes:
- potential switching
- dynamic capturing of ions
- ion storage

Precision Trap (PT):
- seven-electrode trap
- large radius (9mm)
  - Reduced image charge shifts
  - Reduced effects of patch potentials
- homogeneous magnetic field
- **measurement of ν_c**
- spin flip induction (ν_L)

Analysis Trap (AT):
- five-electrode trap
- ferromagnetic CoFe ring: inhomogeneity with $B_2 = 44\frac{kT}{m^2}$
- **detection of spin orientation**

Microwave horn antenna /Laser incoupling
- Spin-flip excitation
- Laser cooling & spectroscopy

Experimental setup

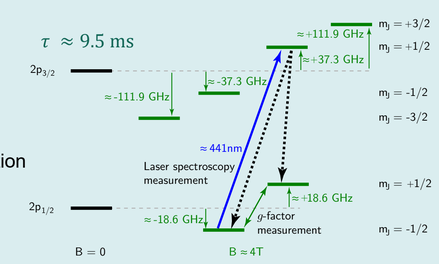


Laser spectroscopy of $^{40}Ar^{13+}$

The development of a new measurement technique [17] combinig laser spectroscopy with the continuous Stern-Gerlach effect (CSGE) allows precision spectroscopy on narrow transitions, being **independent** of fluorescent detection.

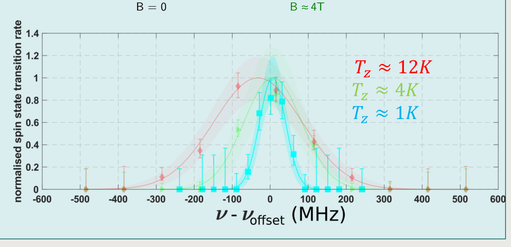
Fine structure spectroscopy in $^{40}Ar^{13+}$:

- Ion is prepared in **"spin down"** state
- Laser excitation near 441nm transition
- Sponteneous decay to dark state with **"spin up"** indicates successfull excitation
- Spin state is analyzed with CSGE



Linewidth dependent on axial ion temperature (Doppler broadening)

$$\Delta f_{FWHM} = f_0\sqrt{\frac{8k_B T\ln(2)}{m_{ion}c^2}}$$



ALPHATRAP Review Paper

For further information check our recently published review paper (60 p.) with a detailed description of the experiment.

The paper is available as open access on: https://doi.org/10.1140/epjst/e2018-800225-2

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Acknowledgements

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Further information: www.mpi-hd.mpg.de/blaum