Max-Planck-Institut für Kernphysik Heidelberg

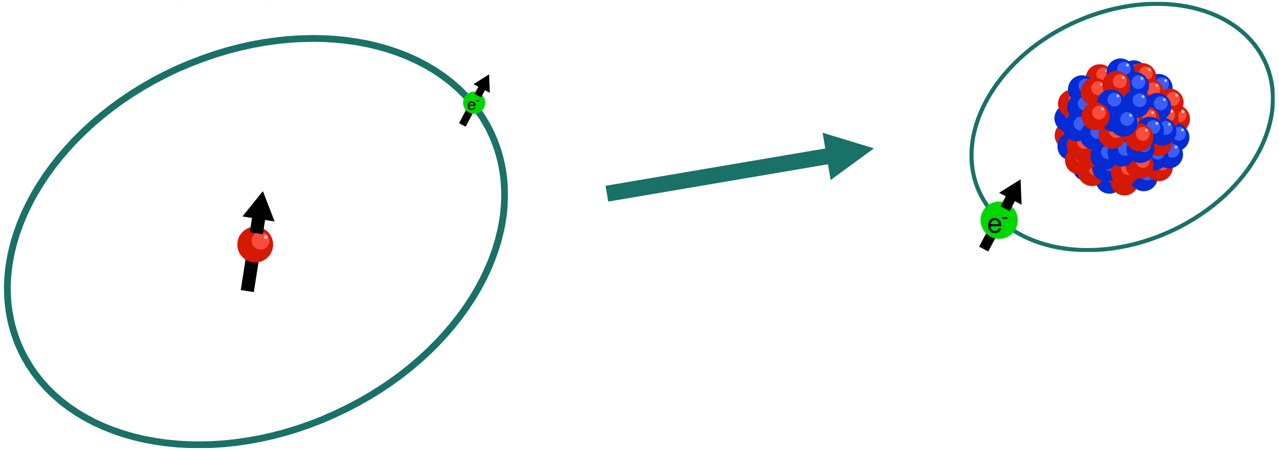
Stringent tests of *ab initio* QED calculations in the Alphatrap experiment

Jonathan Morgner

Precision Physics of Simple Atomic Systems

Hydrogen atom

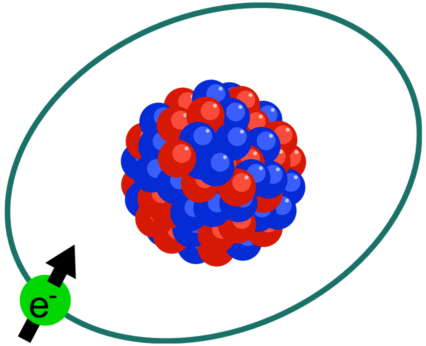
Hydrogen-like ion



- Stronger Coulomb coupling
- Electric field strength reaches values of 10^{16} V/cm

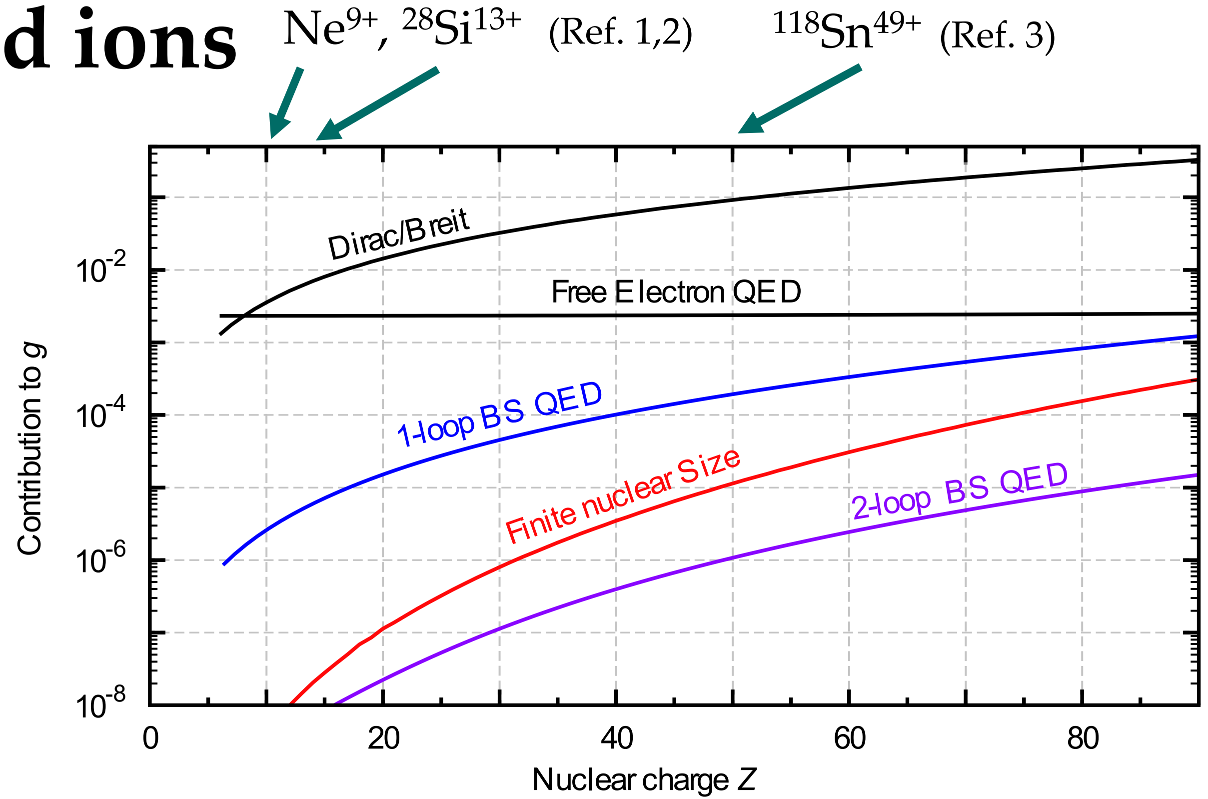
- Well tested and well understood
- We can add complexity to probe other aspects of the atomic theory

Highly charged ions



- ***g* factor** as the observable to probe the underlying theory

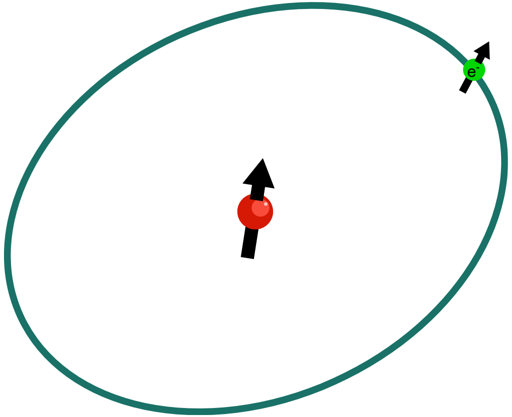
- Bound-state (BS) QED effects scale strongly with Z



[1]Heiße *et al.* PRL **131** (2023), [2]Sturm *et al.* PRL **107** (2011), [3]Morgner *et al.* Nature **622** (2023)

Precision Physics of Simple Atomic Systems

Hydrogen atom



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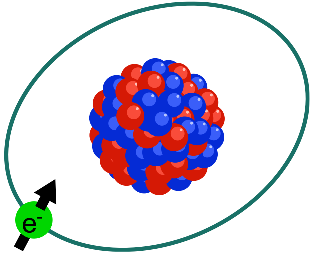
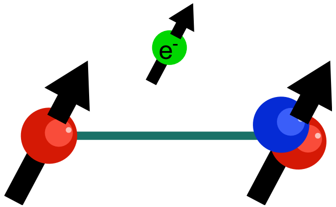


- Stronger Coulomb coupling
- Electric field strength reaches values of 10^{16} V/cm

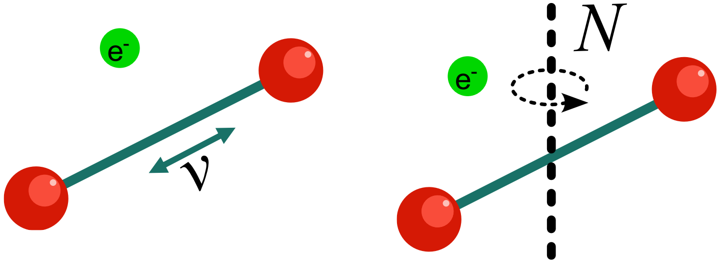
Molecular hydrogen ion



- Simplest available molecule

Why Molecular Hydrogen Ions

$$f_{vib} \sim cR_\infty \sqrt{\frac{m_e}{m_p}}$$



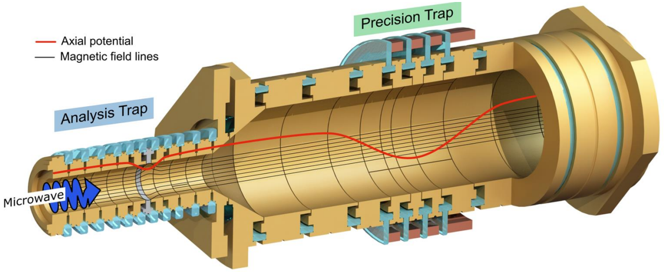
$$f_{rot} \sim cR_\infty \frac{m_e}{m_p}$$

- Simple system → precise theory prediction
- Rovibrational levels give access to fundamental constants
- CPT[1] test comparing H_2^+ and $\bar{H}_2^-$
  - \+ unique and high sensitivities
  - – very low $\bar{H}_2^-$ production rates
  - – Symmetric molecule → no dipole transitions (up to 10^{11} s lifetimes)

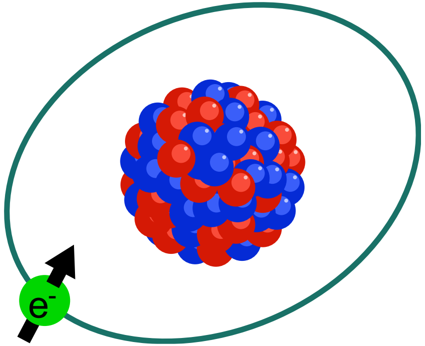
➢ **Single-ion non-destructive state detection and spectroscopy needed**

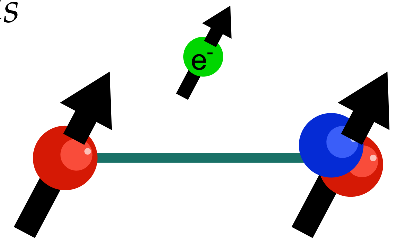
[1]E. Myers, Phys. Rev. A 98, 010101(R) (2018)

Outline



Introduction *Setup* & *Methods*





- *g*-factor measurement of hydrogen-like[1] and lithium-like[2] tin

- Demonstration of non-destructive single ion state detection
- HFS measurement in HD^+

[1]Morgner *et al.*, *Nature* **622** 53-57 (2023)

[2]Morgner *et al.*, submitted

[3]König *et al.*, in preparation

ALPHATRAP setup

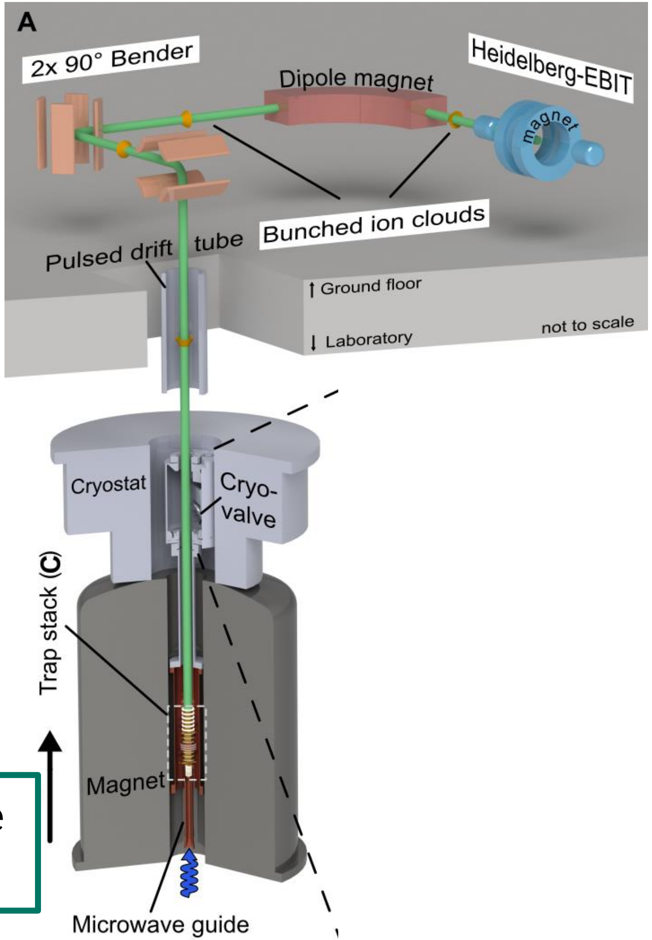
- ➢ Penning-trap with 4-Tesla magnet
- ➢ Cryogenic setup

- ➢ Access to externally produced ions
  - Mini-EBIT ($Z \leq 14$)
  - Heidelberg-EBIT ($Z \leq 55$)
  - Eventually Hyper-EBIT
    (See upcoming talk of Athulya Kulangara Thouttungal George)

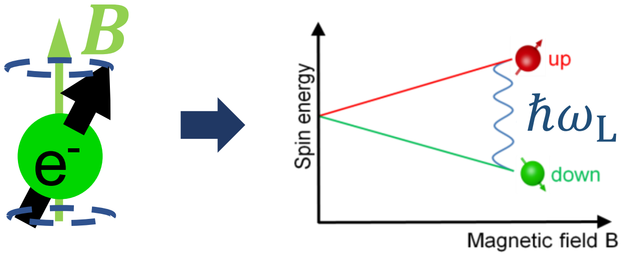
- ➢ room-temperature beamline connects to trap

- ➢ Separated by cryogenic valve
  →Pressure below 10^{-16} mbar

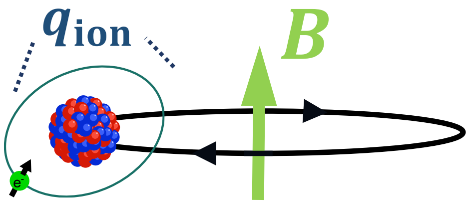
Month long storage of single ions



g-factor Measurement principle



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



$$\omega_c = \frac{q_{ion}}{m_{ion}}B$$

$$\Gamma = \frac{\omega_L}{\omega_c}$$

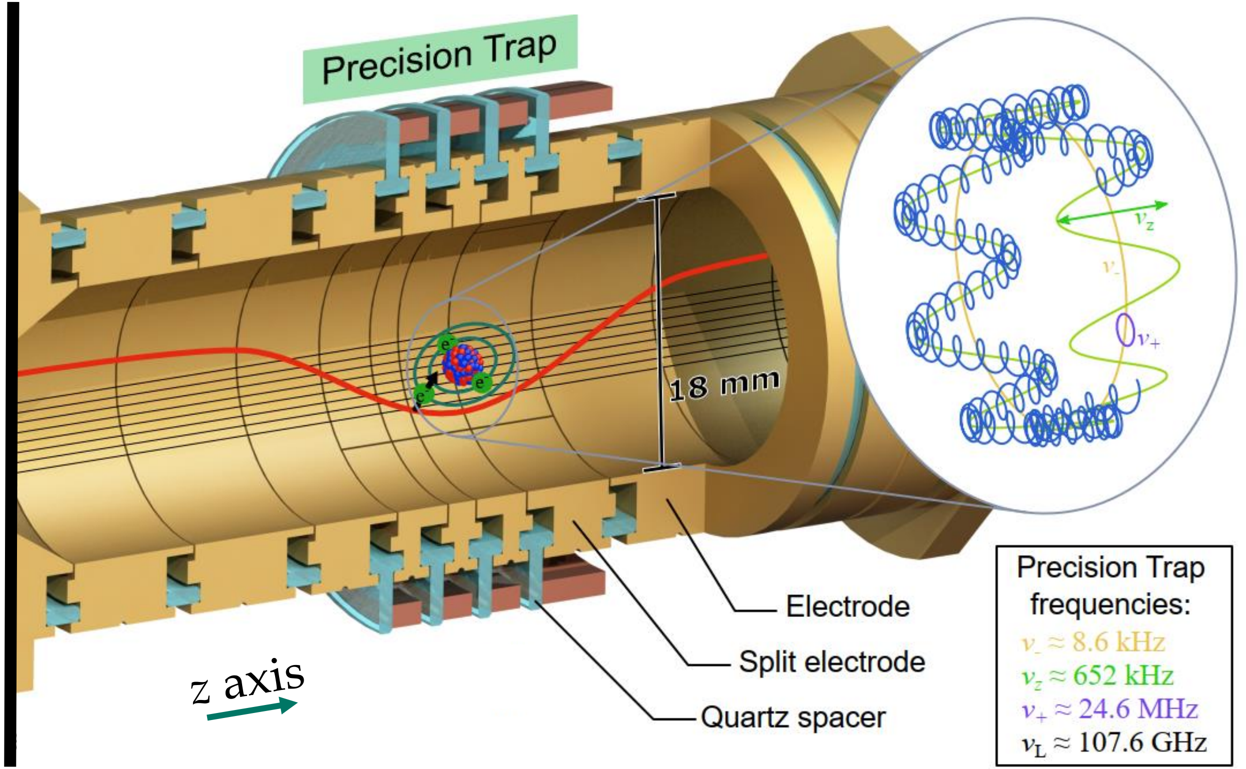
is measured

$$g = 2\frac{\omega_L}{\omega_c}\frac{q_{ion}}{e}\frac{m_e}{m_{ion}}$$

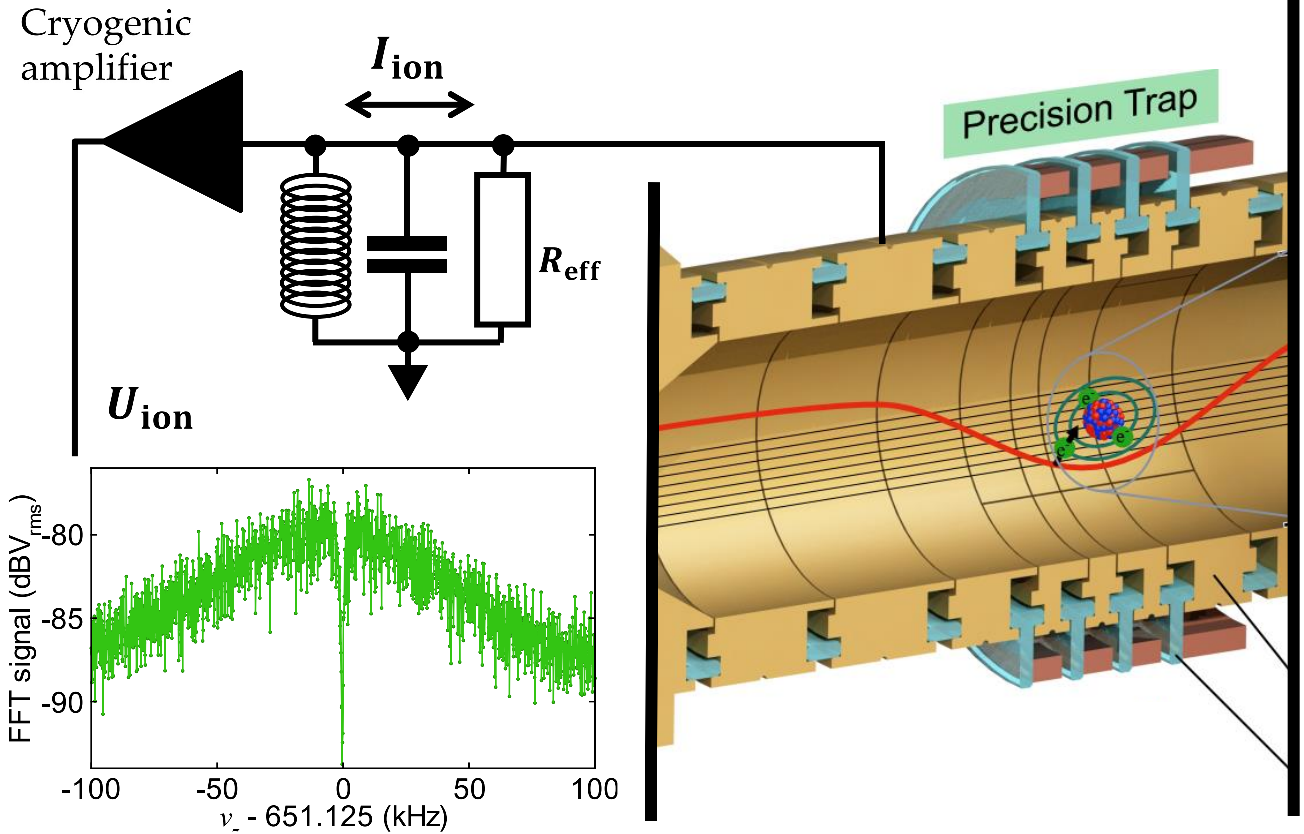
Independent precision measurements

Penning trap

- A combination of $\boldsymbol{E}$ and $\boldsymbol{B}$ field confine the particle in the trap
- Motion splits into three eigenmotions
- Determine ω_c from the ion motion



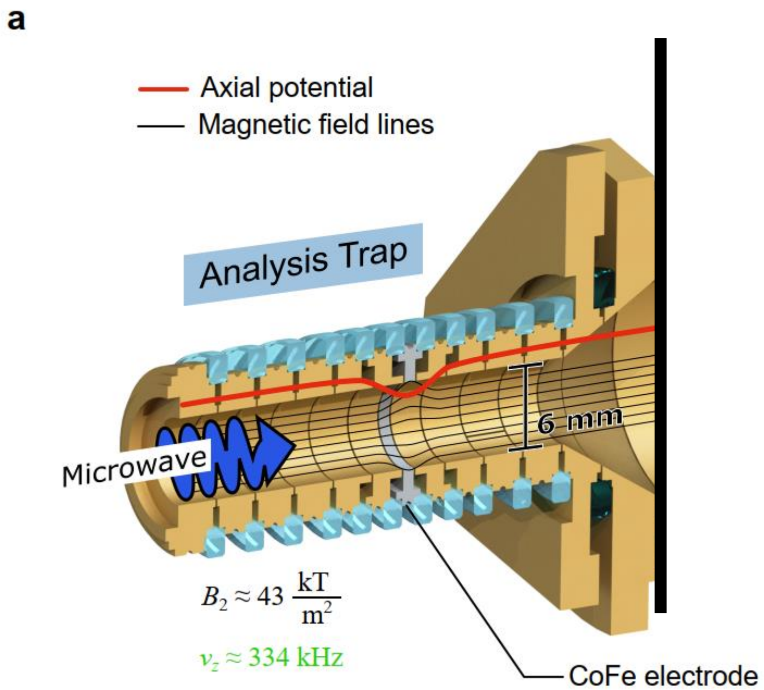
Ion detection

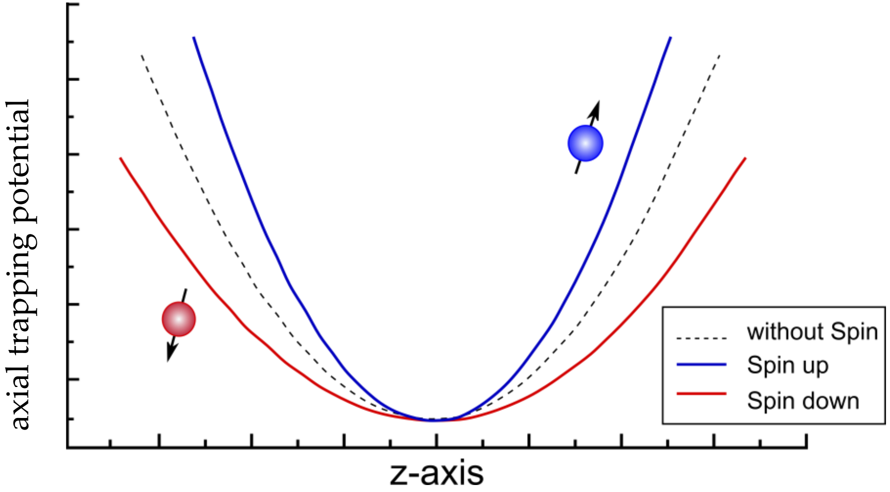


- fA image charge currents
- Cryogenic detector amplifies the signal
- Thermalize the ion to 4 K

Spin-state detection

$$B = B_0 + B_2 \cdot z^2 + \cdots$$



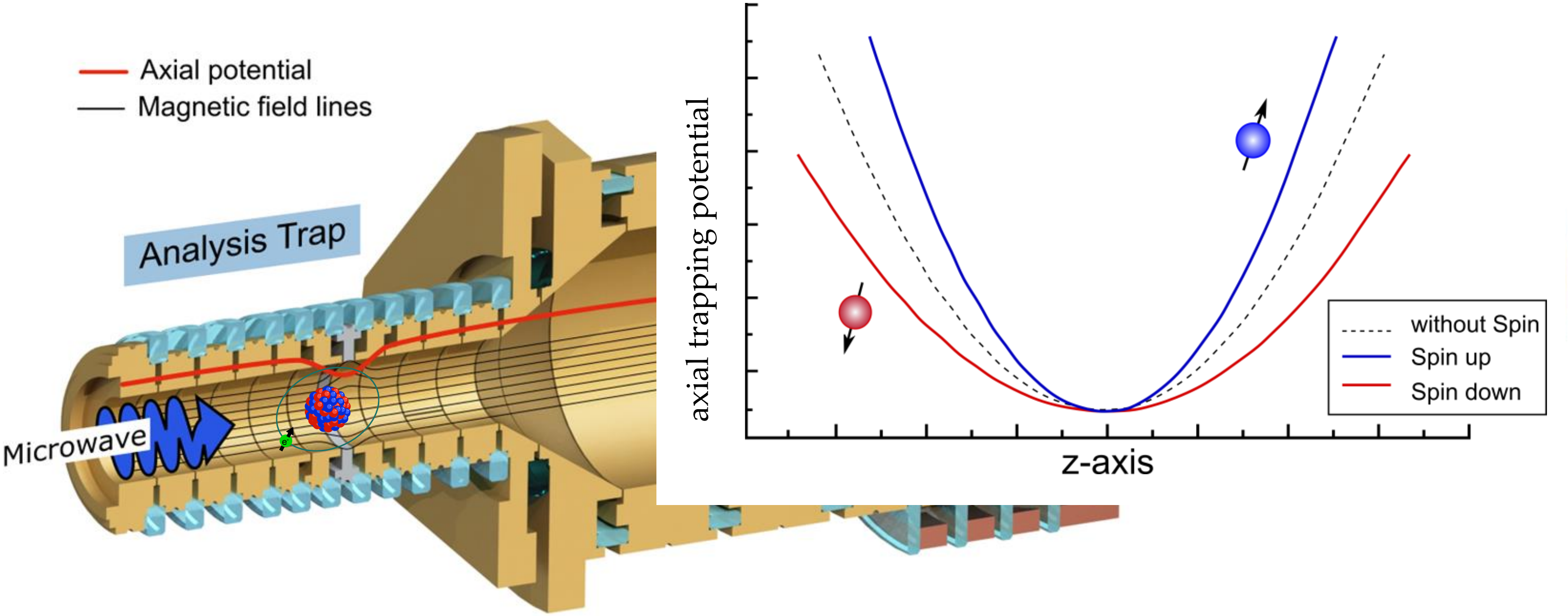


- Magnetic bottle makes the axial frequency spin state dependent
- Driving a spin flip resu… frequency

Non-destructive single-ion spin-state determination

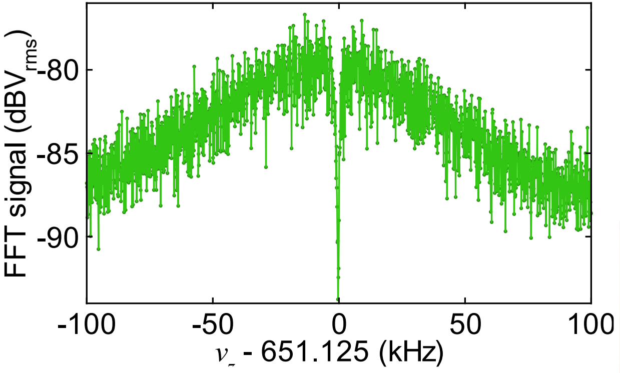
g-factor measurement

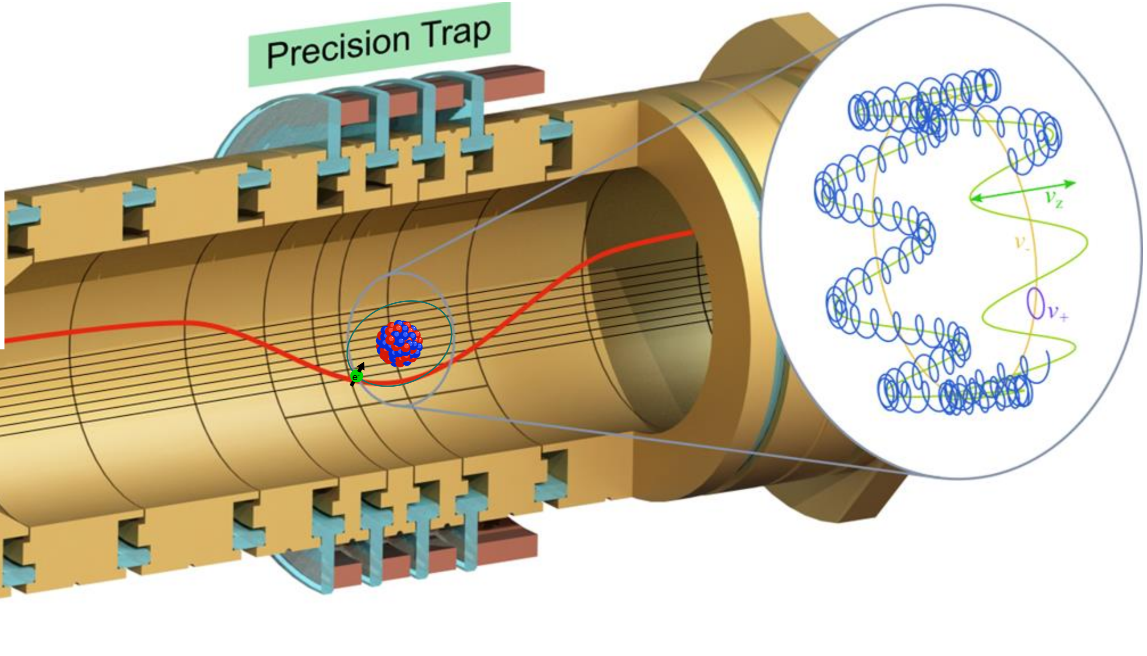
Measure Spinstate → Transport to PT



g-factor measurement

Measure Spinstate → Transport to PT → Measure ν_c Inject MW ν_{MW} → Transport to AT





Drive transition with microwave or a laser

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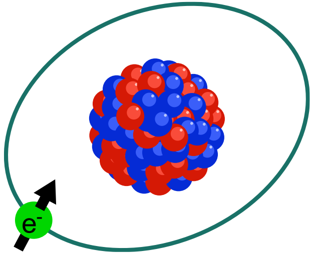
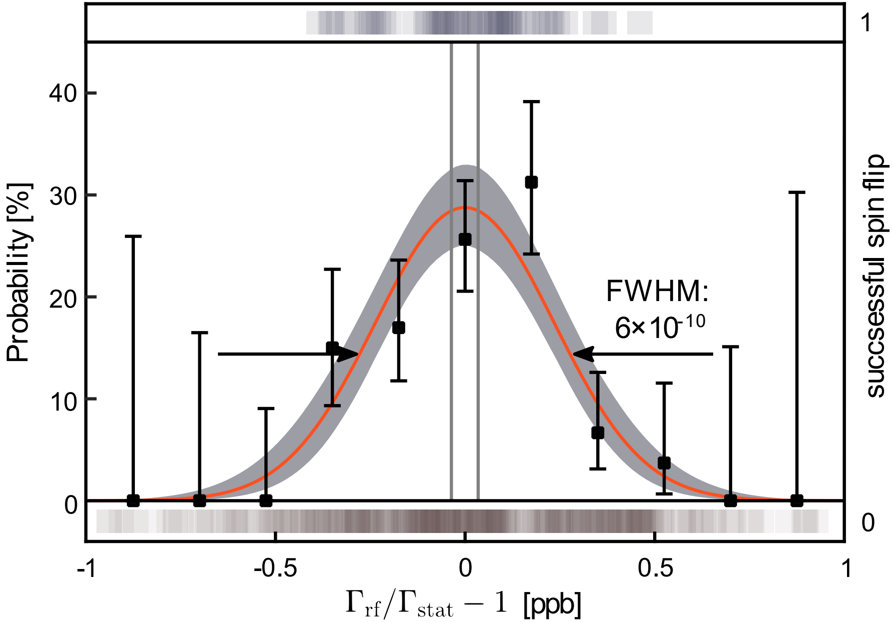


- Stronger Coulomb coupling
- Electric field strength reaches values of 10^{16} V/cm

Molecular hydrogen ion

- Simplest available molecule

$^{118}Sn^{49+}$ *g* factor



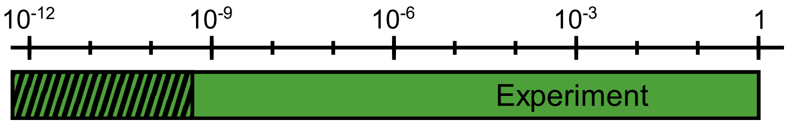
- Transistion probability as a function of $\Gamma = {}^{\nu_L}/_{\nu_c}$
- Maximum-likelihood fit of the data

$$g = 2\frac{\boldsymbol{\omega}_L}{\boldsymbol{\omega}_c}\frac{q_{ion}}{e}\frac{m_e}{m_{ion}}$$

$$g_{Exp} = 1.910\,562\,059\,0(9) \longrightarrow 5 \times 10^{-10}$$

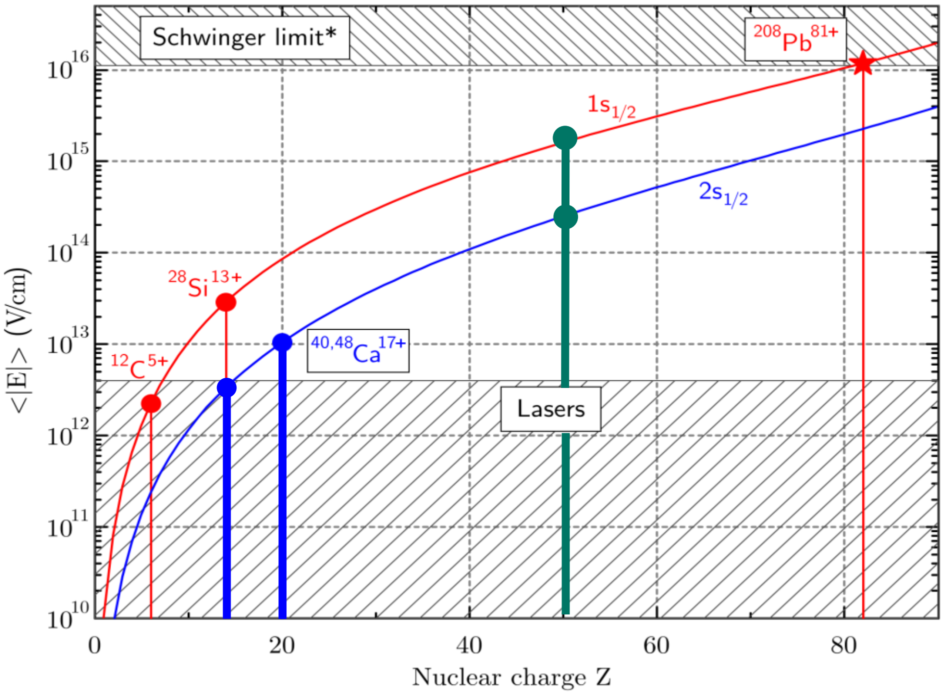
Morgner *et al*. Nature **622** (2023)

$^{118}Sn^{49+}$ *g* factor



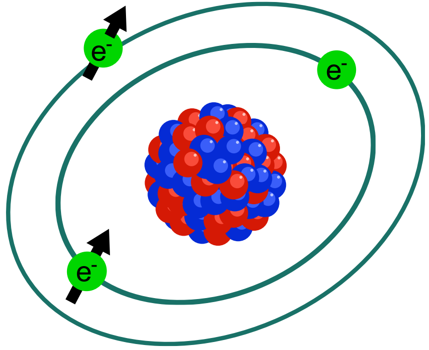
$$g_{\mathrm{Exp}} = 1.910\,562\,059\,0(9)$$

$$g_{\mathrm{Theo}} = 1.910\,561\,821\,0(2988)$$



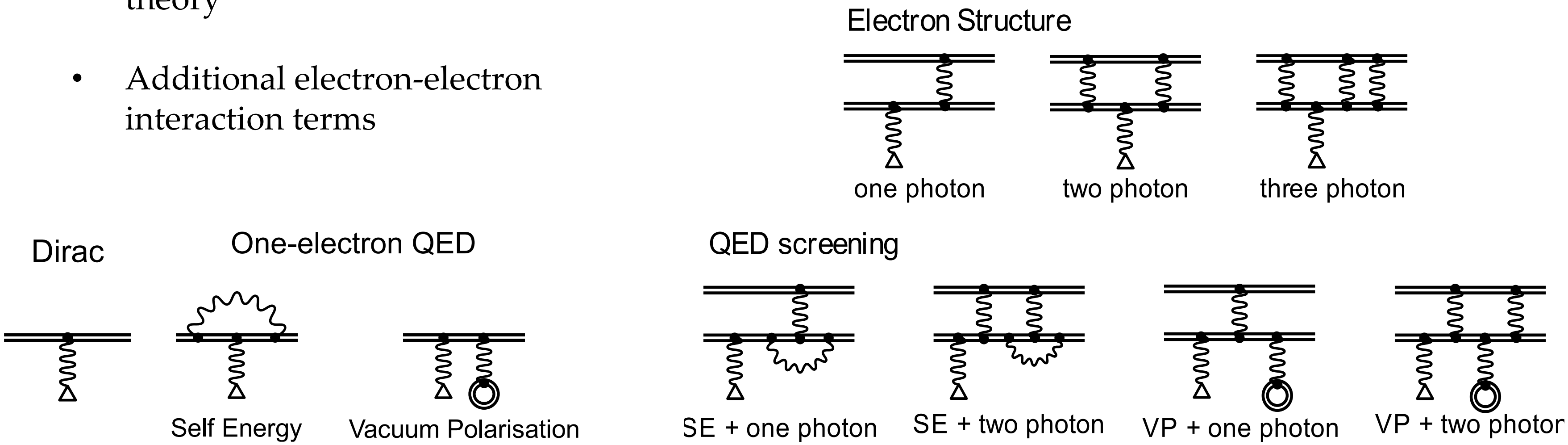
Sturm *et al.* EPJ The ALPHATRAP Experiment (2019)

Lithium-like tin



$g_{\text{Exp}}(2s) = 1.980\ 354\ xxx(1)$[1]

- Structure similar to hydrogen-like theory
- Additional electron-electron interaction terms



[1]Morgner *et al.*, submitted (2024)

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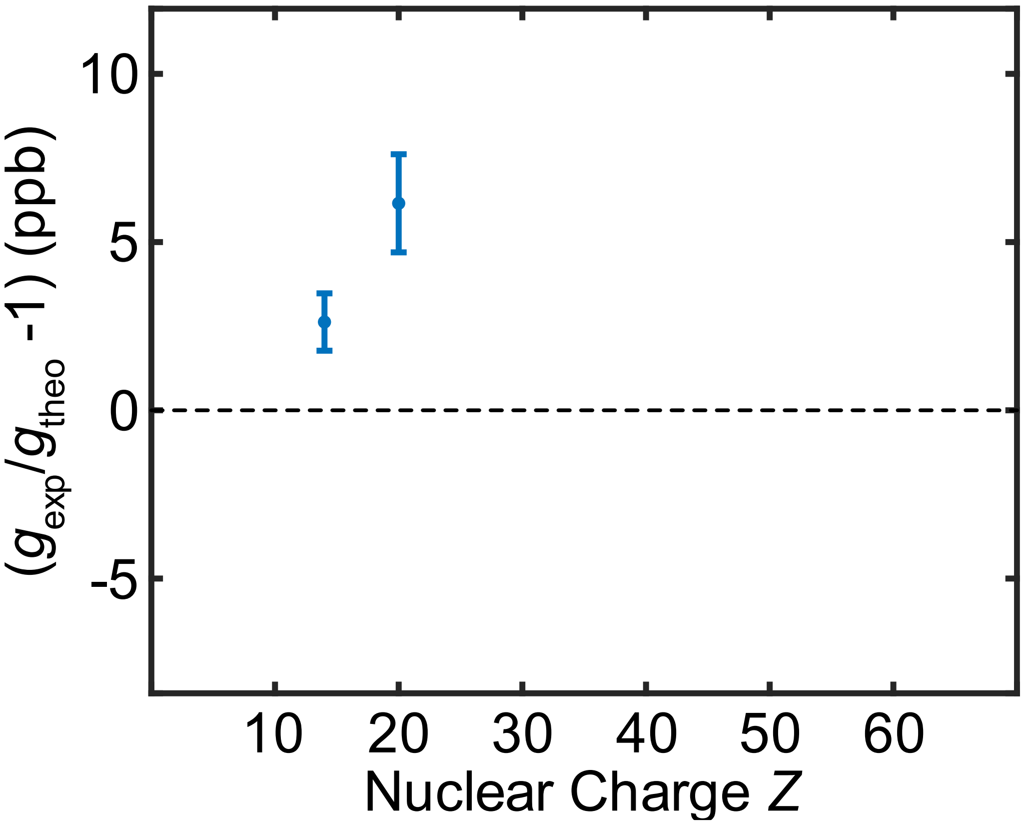


[1]Morgner *et al.*, submitted (2024)

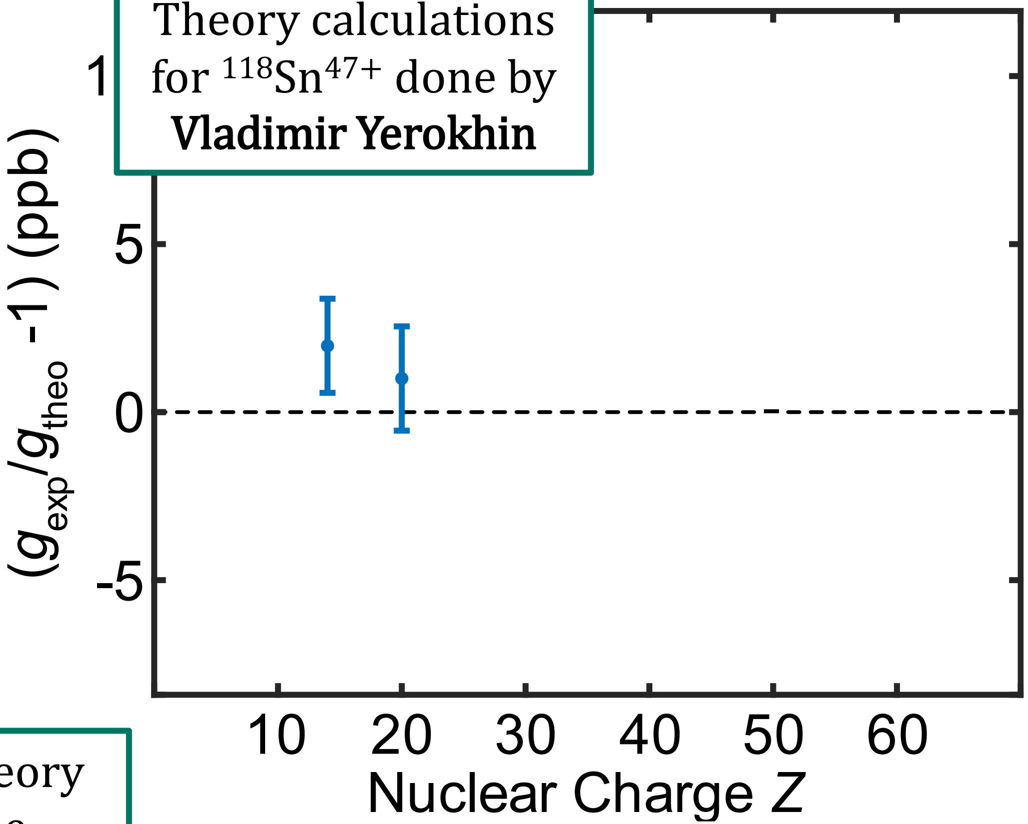
Lithium-like tin

$g_{\mathrm{Exp}}(2s) = 1.980\ 354\ xxx(1)$[1]

- Structure similar to hydrogen-like theory
- Additional electron-electron interaction terms
- New Theory calculations seem to resolve the discrepancy in the low-Z measurements[2]

Independent test of the **new** theory in a so far unexplored regime

Theory calculations for $^{118}Sn^{47+}$ done by **Vladimir Yerokhin**



[1]Morgner *et al.*, submitted (2024), [2]Kosheleva *et al.*, PRL (2022)

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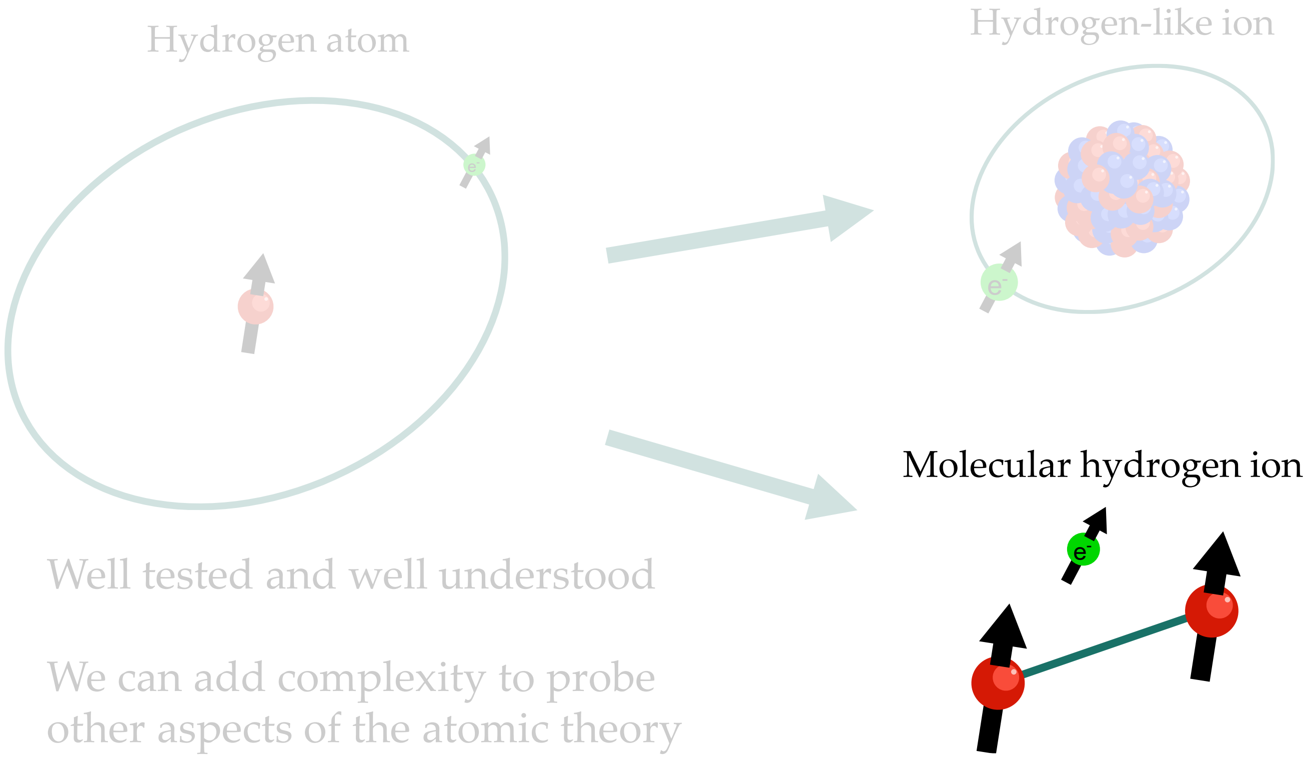

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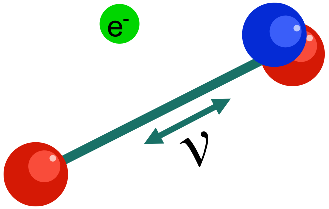
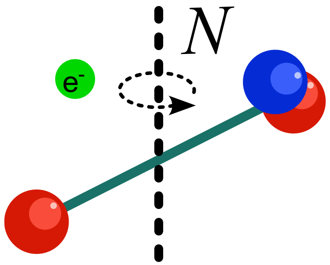
Hyperfine Structure of HD^+

$$f_{vib} \approx cR_\infty \sqrt{m_e\left(\frac{1}{m_d} + \frac{1}{m_p}\right)}$$





$$f_{rot} \approx cR_\infty m_e\left(\frac{1}{m_d} + \frac{1}{m_p}\right)$$

Why:

- **Excited state lifetimes < 140 s**
  - ground state preparation
- **Rovibrational measurements:**
  - determine fundamental constants:
  - m_p/m_e at 20 ppt
  - Deviations up to 9 σ between theory and experiment[1-4]

Goals:

- ➢ Demonstrate single-ion, non-destructive spectroscopy
- ➢ Measure hyperfine structure

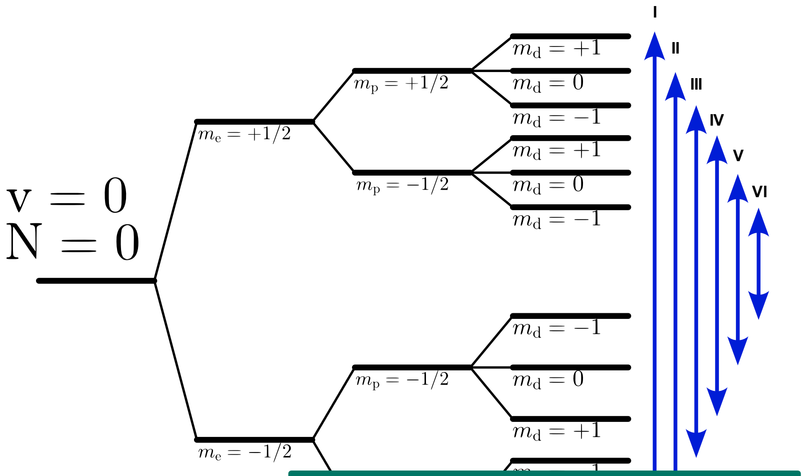
[1]S. Alighanbari *et al.*, *Nature* **581** (2020), [2]S. Patra *et al.*, *Science* **369** (2020), [3]I. V. Kortunov *et al.*, *Nat. Phys*. vol. **17** (2021), [4]S. Alighanbari *et al.*, *Nat. Phys.*, vol. **19** (2023)

Hyperfine Structure of HD$^+$

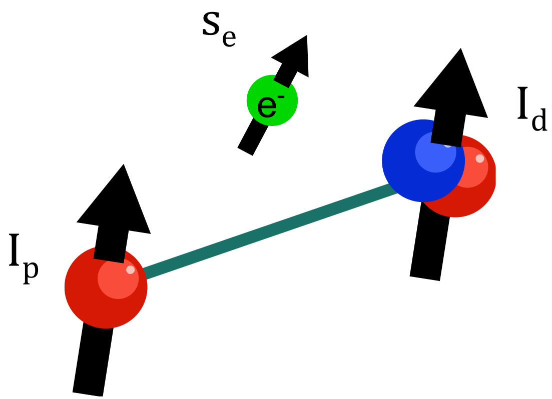
Project of Charlotte König

$$E \approx -\mu_B \mathbf{g}_e \mathbf{B} s_e - \mu_B \mathbf{g}_p \mathbf{B} I_p - \mu_B \mathbf{g}_d \mathbf{B} I_d + \mathbf{E}_4 s_e I_p + \mathbf{E}_5 s_e I_d$$

ν_L(**I - IV**)= 112.139-113.349 GHz



Stringent test of HFS theory



	$g_e(0,0)$	$E_4(0,0)$ [kHz]	$E_5(0,0)$ [kHz]
This work	-2.0022785*xxxx*(xx)	925395.*xxx*(xx)	142287.*xxx*(xx)
Theory	-2.00227846(10) [1]	925394.16(86) [2]	142287.556(84) [2]

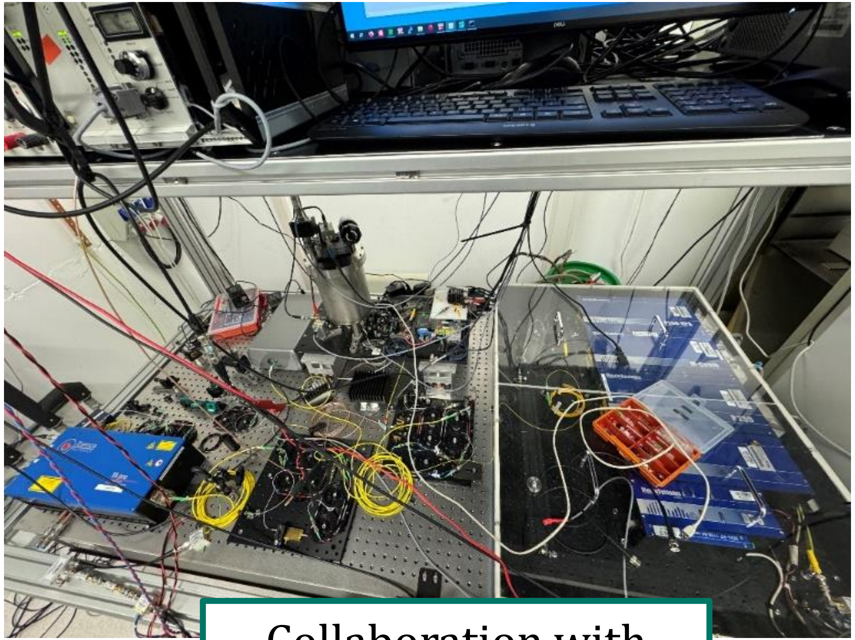
[1]R.A. Hegstrom, *Phys. Rev. A* **19**, 17 (1979), [2]J. P. Karr *et al.*, *Phys. Rev. A* **102**, 052827 (2020)

Next Steps: Laser Spectroscopy of HD^+

Ongoing:

Rovibrational spectroscopy of HD^+

First step: 1.15 μm for (v=0, N=0) -> (v=5, N=1)



- ➢ Perform single-ion non-destructive rovibrational spectroscopy of H_2^+

Collaboration with Stephan Schiller from the Uni Düsseldorf

Summary

Hydrogen-like tin:

→ Stringent test of QED in the extremely strong fields of the hydrogen-like tin nucleus

Lithium-like tin:

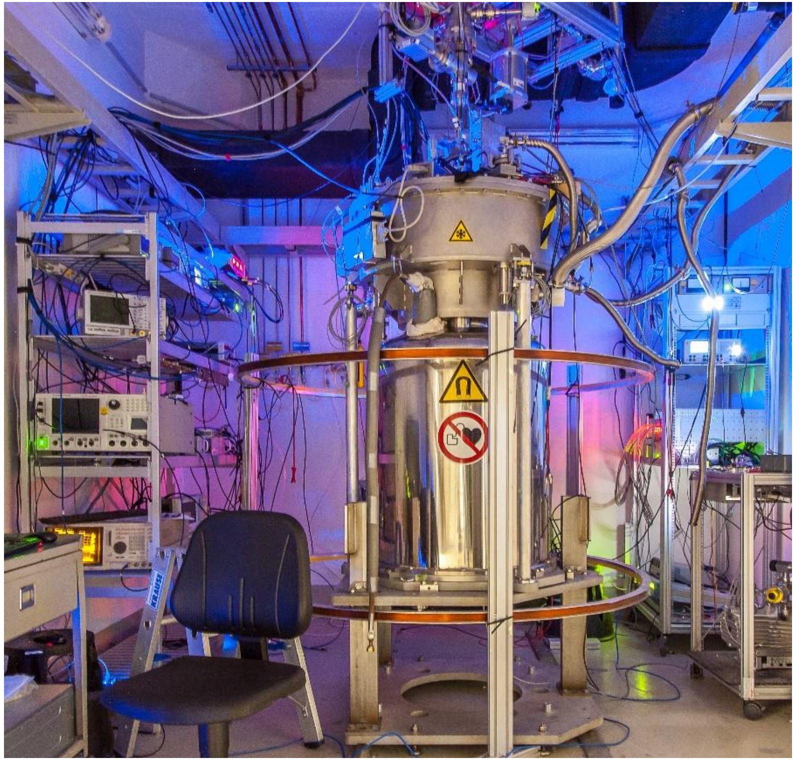
→ Test the new e-e interaction calculations with a new measurement in an unexplored regime

HD^+ HFS spectroscopy:

→ Non-destructive state detection

→ Testing fundamental theory relevant for fundamental constant m_p/m_e

ALPHATRAP lab



Thank you

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- Klaus Blaum

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- Vladimir Yerokhin
- Bastian Sikora
- Chunhai Lyu
- Vincent Debierre
- Christoph Keitel
- Dimitar Bakalov

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- Victor Vogt
- Stephan Schiller

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α TRAP

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HITRAP