The ALPHATRAP g-factor experiment: testing bound-state QED using highly-charged ions

EMMI Physics Day 2019

GSI Darmstadt

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HITRAP

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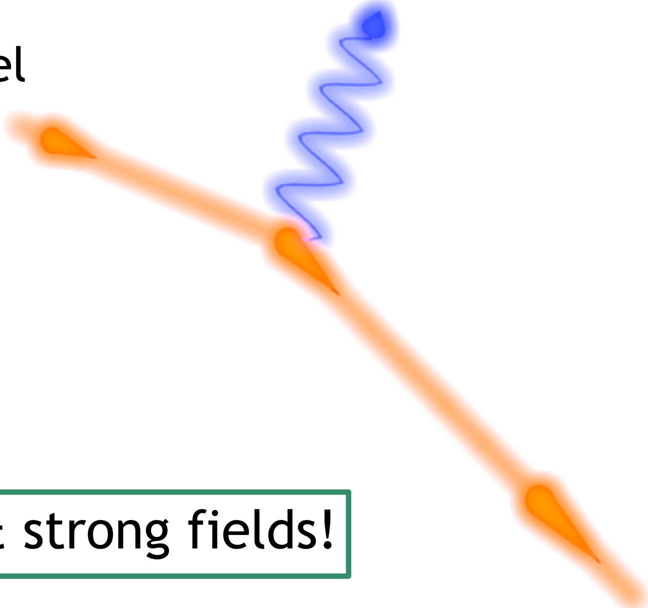
Quantum Electrodynamics (QED)

Quantum Electrodynamics (QED), the theory of light and matter, is tested and proven in the lab

Richard P. Feynman

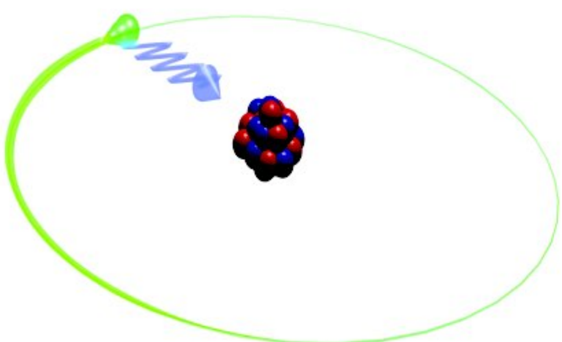
- Most successful theory in the Standard Model
- Prediction of physical observables
- All accessible field scales
- Experiments consistent with theory
- Non-linear QED processes?
  Photon-photon interaction

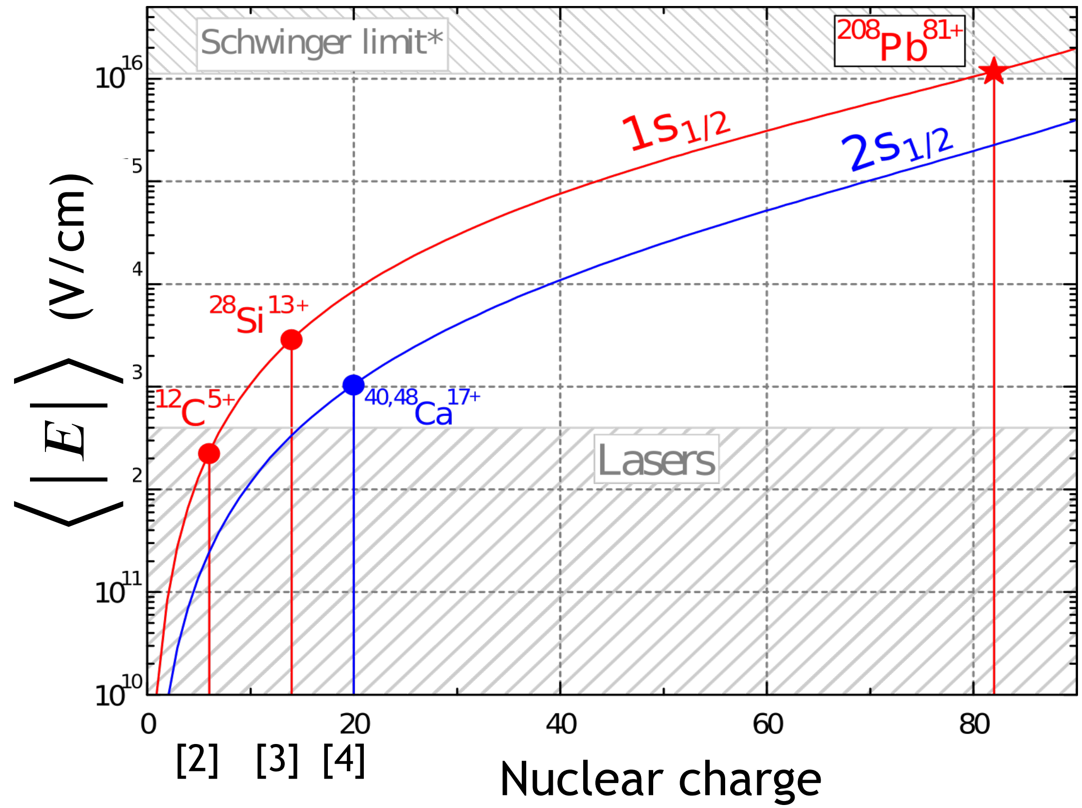


ALPHATRAP: Combine high precision & strong fields!

Testing the Standard Model with ALPHATRAP

$$\vec{\mu} = -g\mu_B\frac{\vec{s}}{h}$$



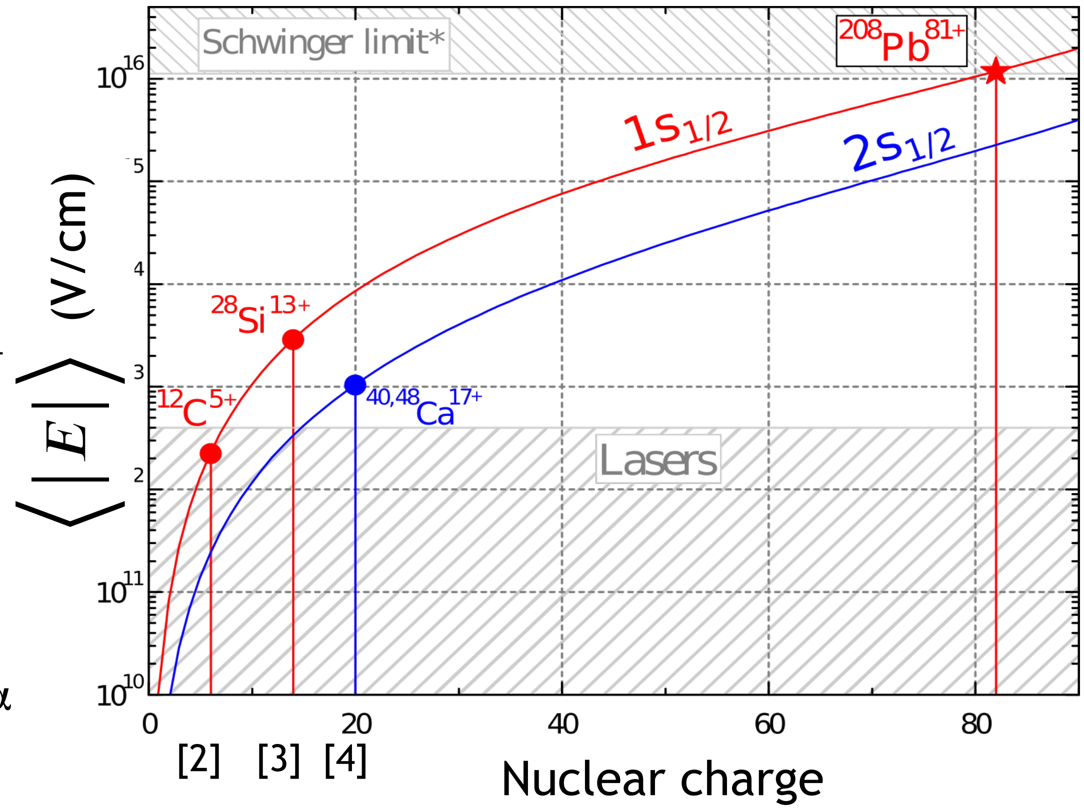


[1] H. Häffner, et al., *Phys. Rev. Lett.* 85, 5308 (2000)
J.Verdu, et al., *Phys. Rev. Lett.* 92, 093002 (2004)
[2] S. Sturm, et al., *Nature* 506, 7489 (2014)
[3] S. Sturm, et al., *Phys. Rev. Lett.* 107, 023002 (2011)
[4] F. Köhler, et al. *Nat. Comm.* 7, 10246 (2016)

Testing the Standard Model with ALPHATRAP

$$\vec{\mu} = -g\mu_B \frac{\vec{s}}{h}$$

- Follow-up experiment of the Mainz *g*-factor experiment
- High-precision test of BS-QED in strong fields, up to $^{208}Pb^{81+}$
- Strongest *E*-fields achievable in high Z nuclei
- Determination of fundamental constants:
  e.g. electron mass [1]
  fine structure constant α



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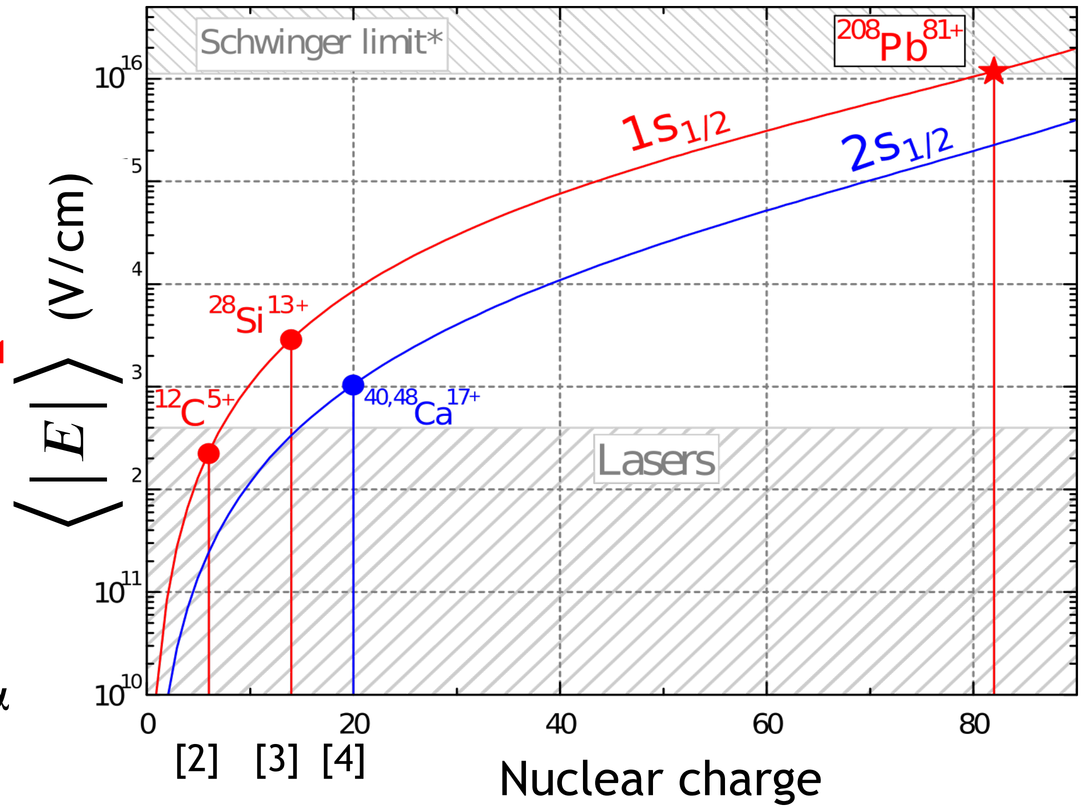

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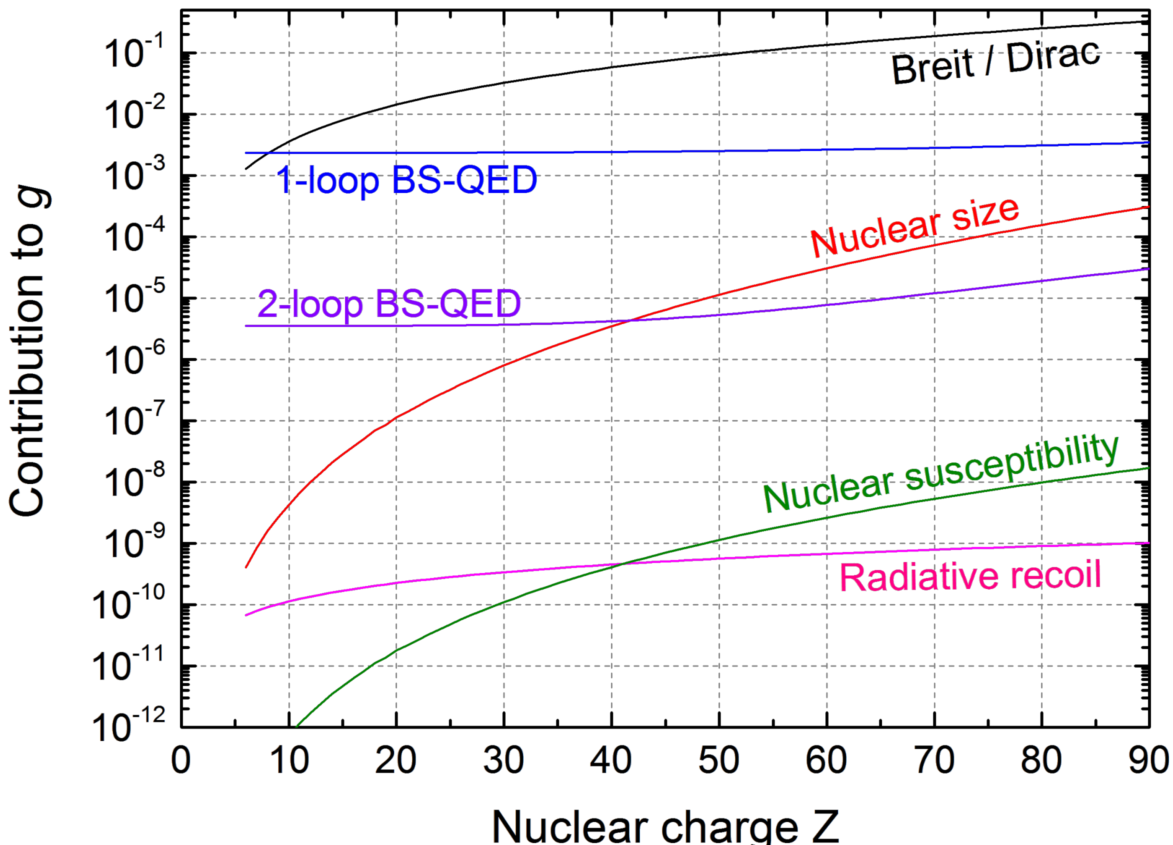
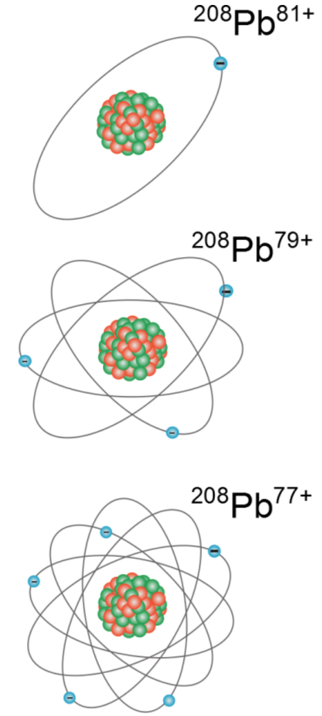
g-factor of HCI

$$\vec{\mu} = -\, g \mu_B \frac{\vec{s}}{h}$$

$$g = g_{\text{Dirac}} + \Delta\, g_{\text{QED}} + \Delta\, g_{\text{nucl}} + \Delta\, g_{\text{int}} + \ldots$$

Hydrogenlike ions





[Z. Harman et al. (2016)]

g-factor of HCI

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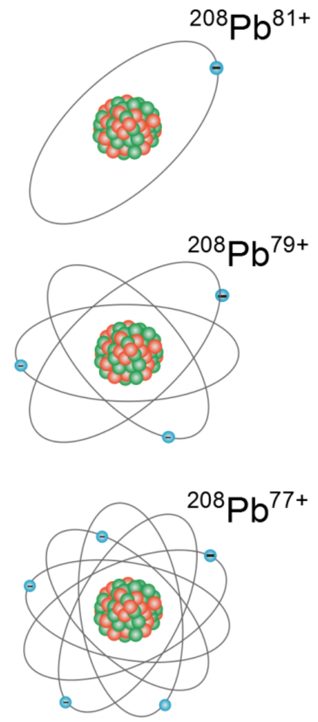
- <u>H-like to Li-like ions:</u> → **QED test**

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

Suppression of nuclear contributions

- <u>H-like to B-like ions:</u> → **Fine structure const. α**

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



[Shabaev et al., PRL 96, 253002 (2006)]

g-factor of $^{40}Ar^{13+}$

$$\vec{\mu} = -g\mu_B \frac{\vec{s}}{h}$$

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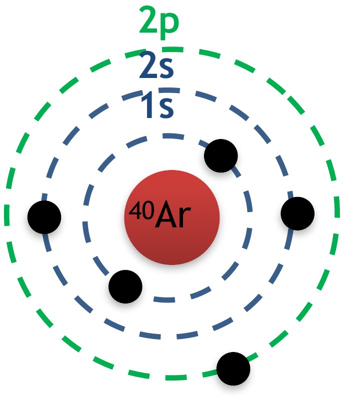
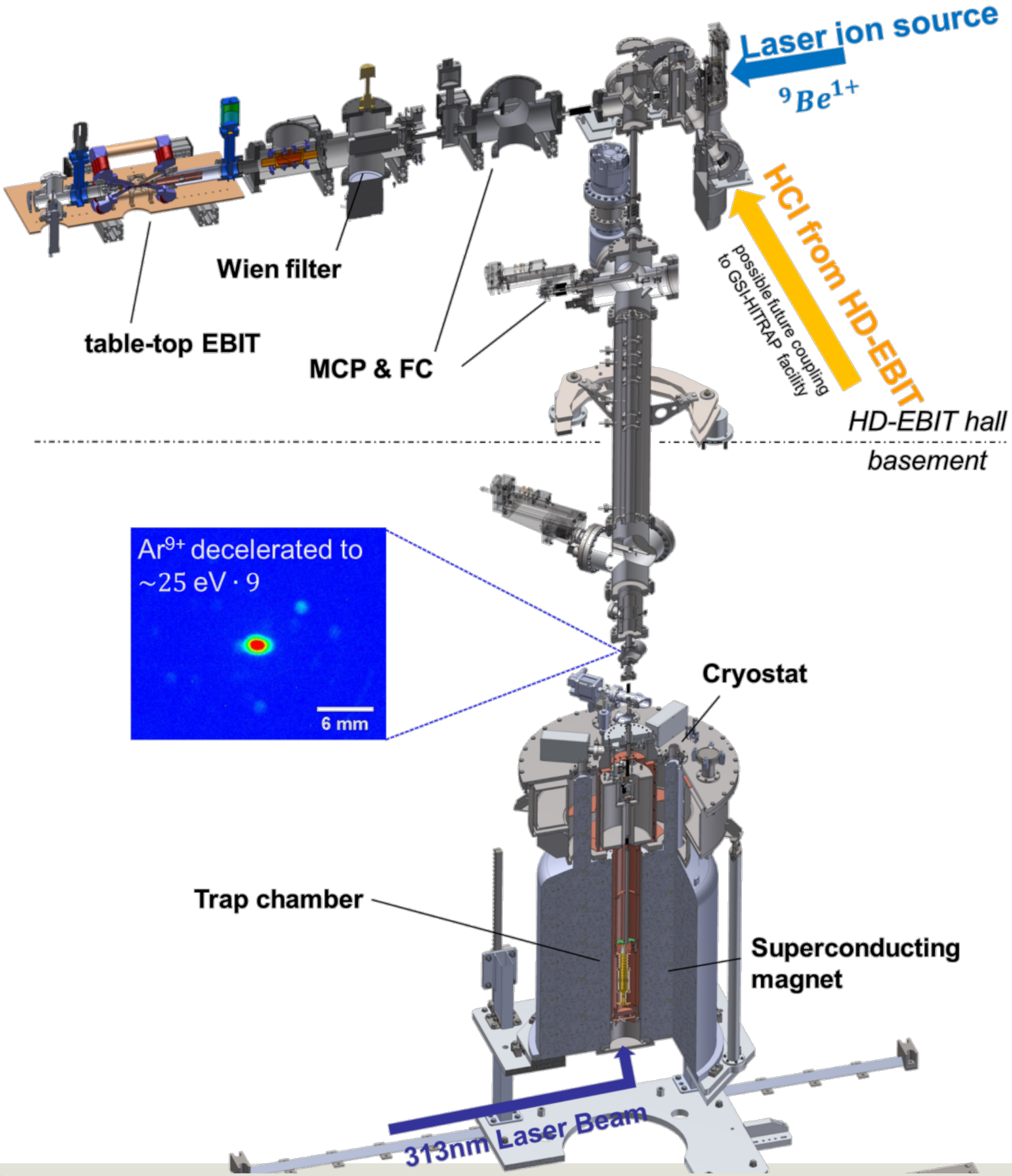


First high-precision *g*-factor measurement of 5-electron HCI

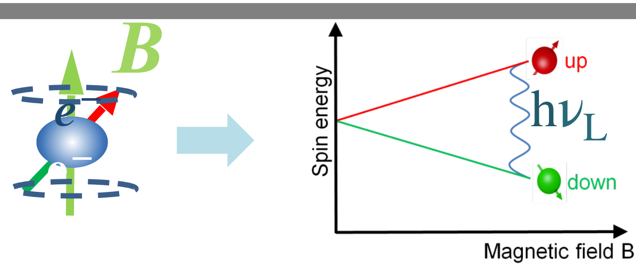
- ➢Bound electron spin-orbital coupling
- ➢Many-electron QED contribution(Δg_{int})
- ➢Higher order (cubic) Zeeman effect [1]
- ➢First measurement of ALPHATRAP
- ➢*g*-factor difference between B- and H-like ions [2]
  - Reduced nuclear-structure effect
  - Fine structure constant α determination

[1] D. von Lindenfel et al., *Phys. Rev. A* 87, 023412 (2013)
[2] V. Shabaev et al., *Phys. Rev. Lett.* 96, 253002 (2006)

Experimental Setup

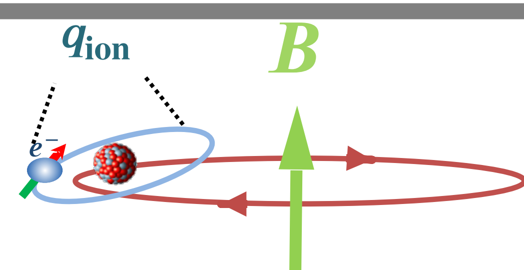


g-factor determination



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

Determine the Larmor frequency
in a well-known magnetic field



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

Measure the free cyclotron frequency
to determine the magnetic field

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

to be measured

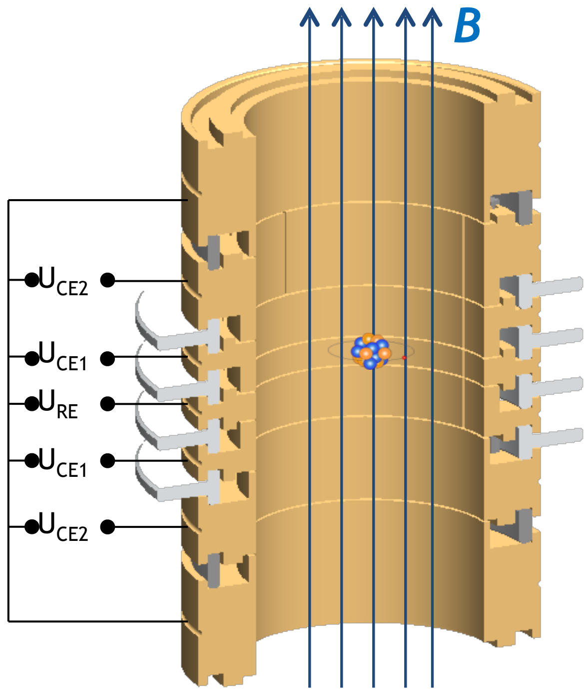
$$\Gamma = \frac{\nu_L}{\nu_c}$$

Independent precision experiments

Penning trap

<u>Requirements:</u>

- Single, cold ion
- Homogeneous magnetic field: ~ **4 T**
- Cryogenic temperature: ~ **4.2 K**
- Long storage times: ~ **months**
- Extremely high vacuum: ~ $\mathbf{10^{-17}}$ **mbar**



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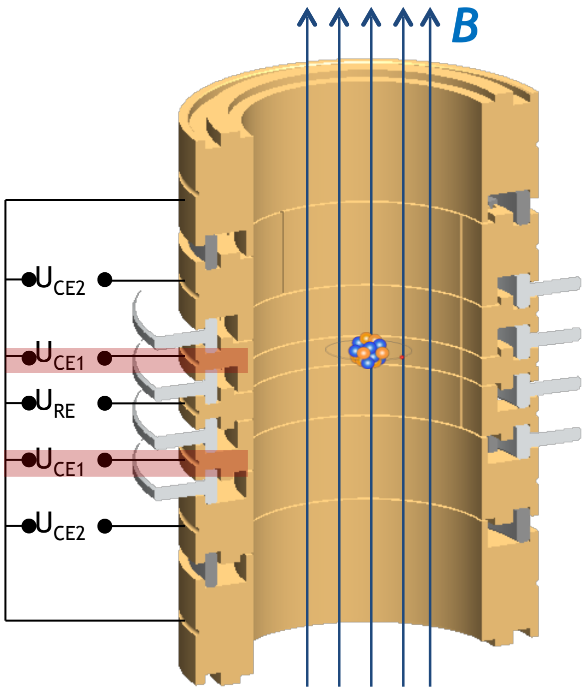

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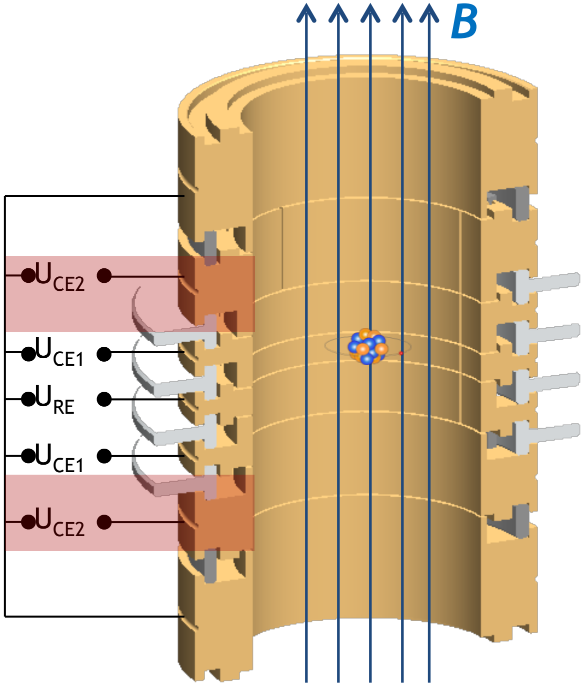

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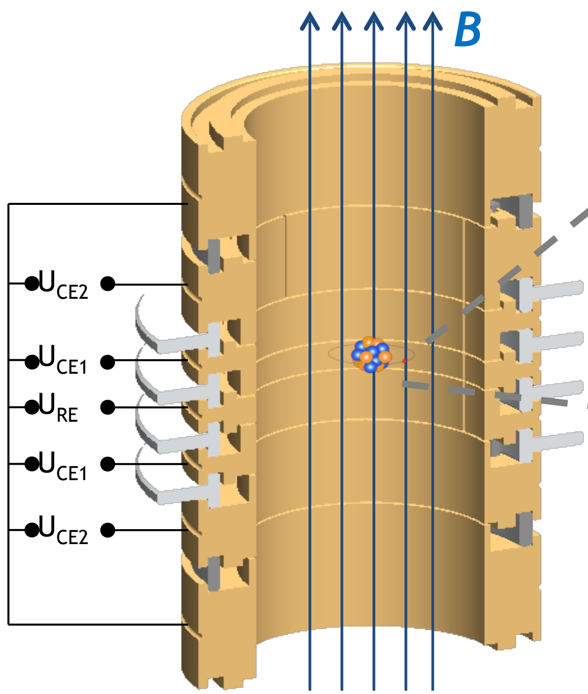

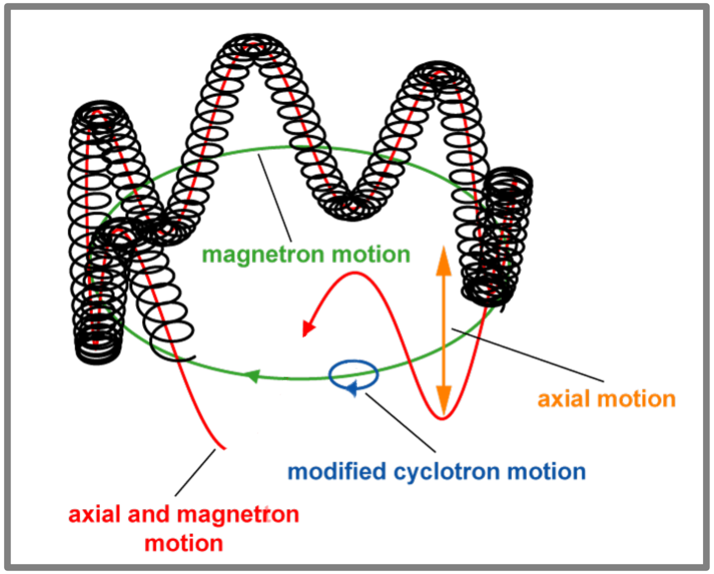

$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$$

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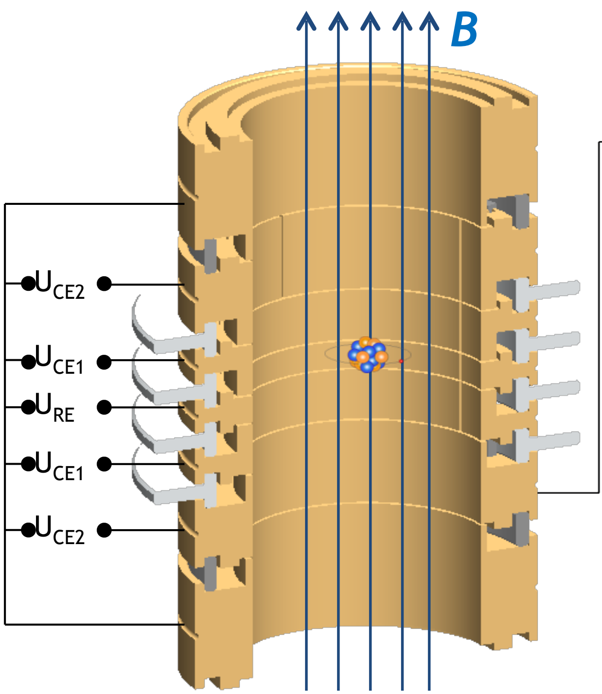
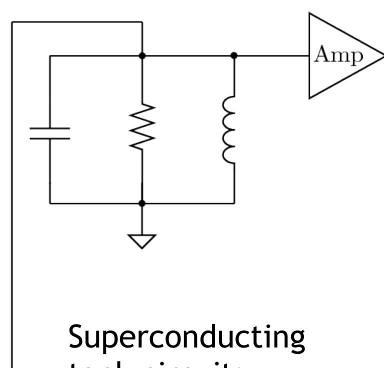
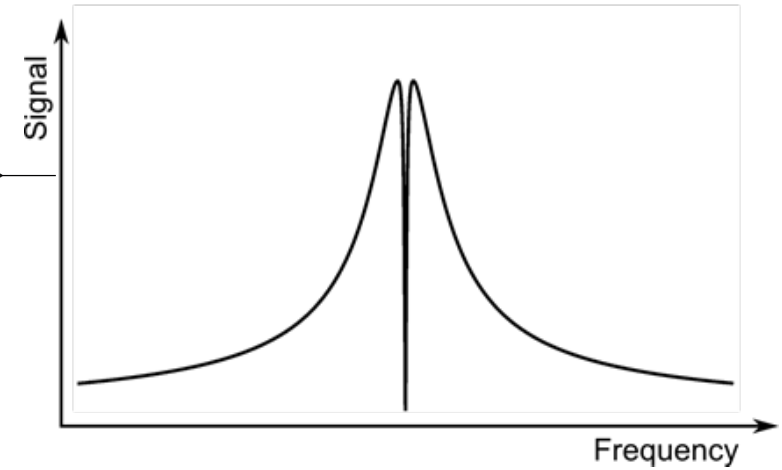




Superconducting tank circuit:

$f = 650$ kHz

$Q = 40000$



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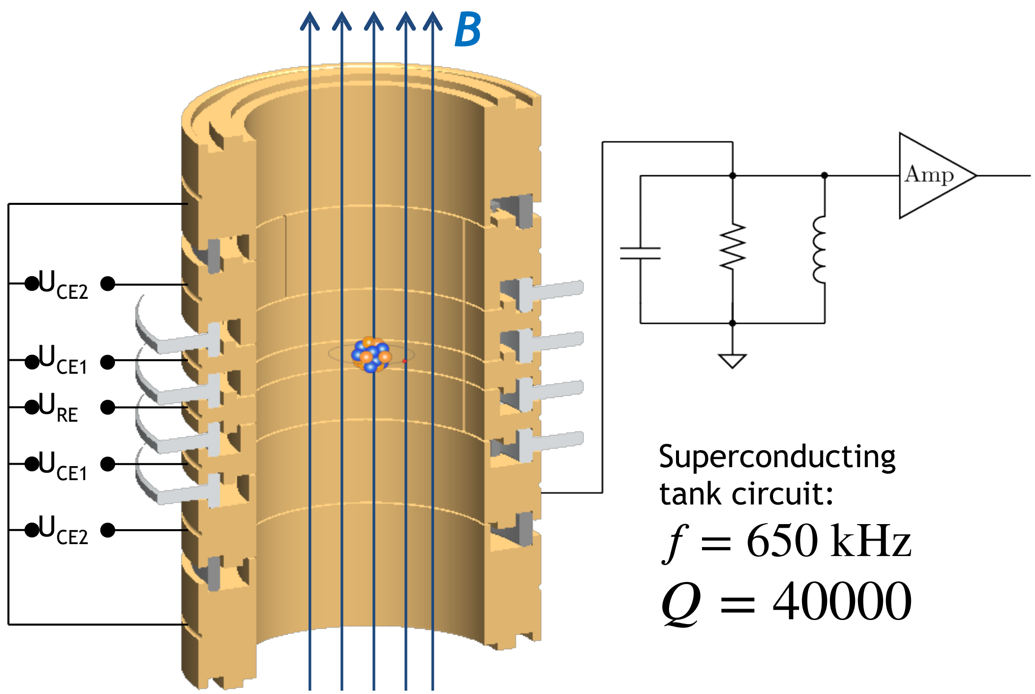

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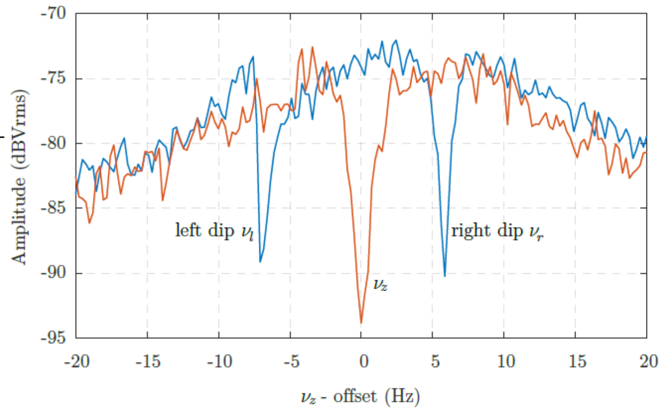
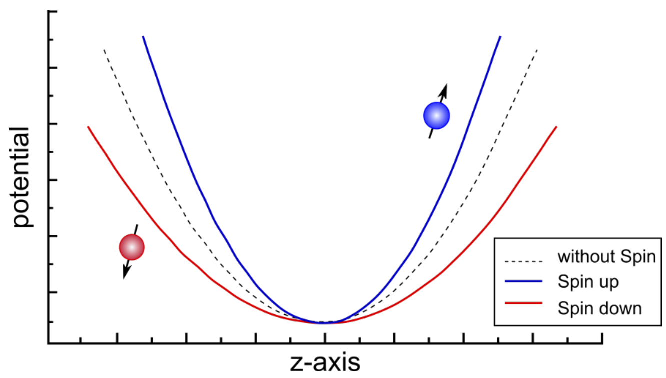


$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$$

Penning trap - spin state detection

Continuous Stern-Gerlach effect:

axial frequency difference between "up" and "down" spin orientation

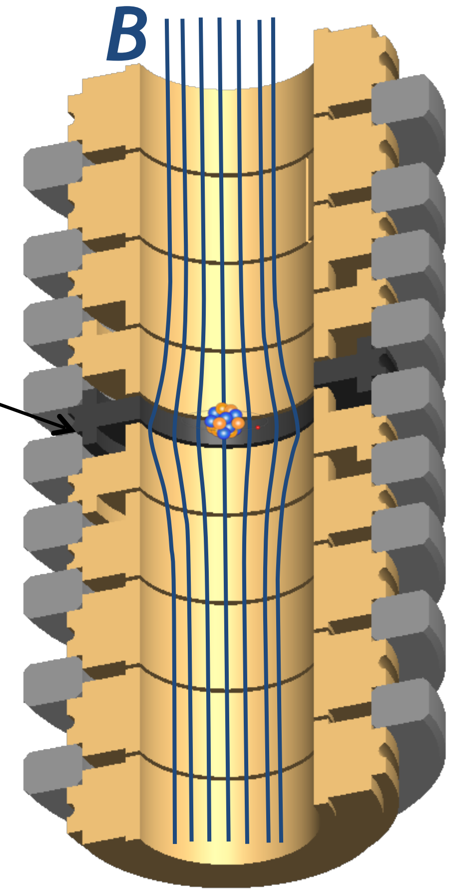


$$\Phi_z^{mag} = \pm\mu_z\left[B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)\right]$$

Ferromagnetic ring

- Magnetic bottle
- B_2 ~ 44000 T/m²

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



	$^{12}C^{5+}$	$^{28}Si^{13+}$	$^{40}Ca^{19+}$	$^{40}Ar^{13+}$	$^{208}Pb^{81+}$	$^{208}Pb^{77+}$
$\Delta\nu_z$	3Hz	1.3Hz	910mHz	300mHz	180mHz	60mHz

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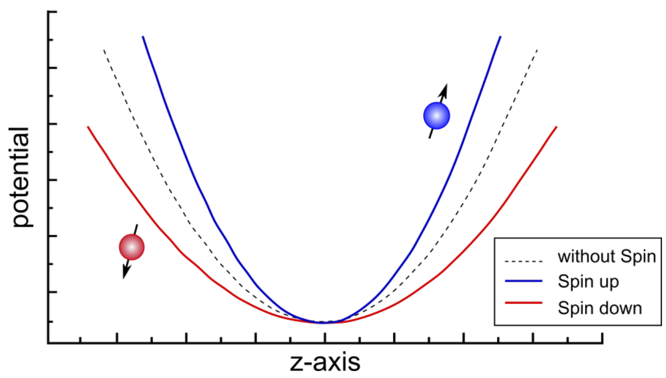

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<u>Ferromagnetic ring</u>

- Magnetic bottle
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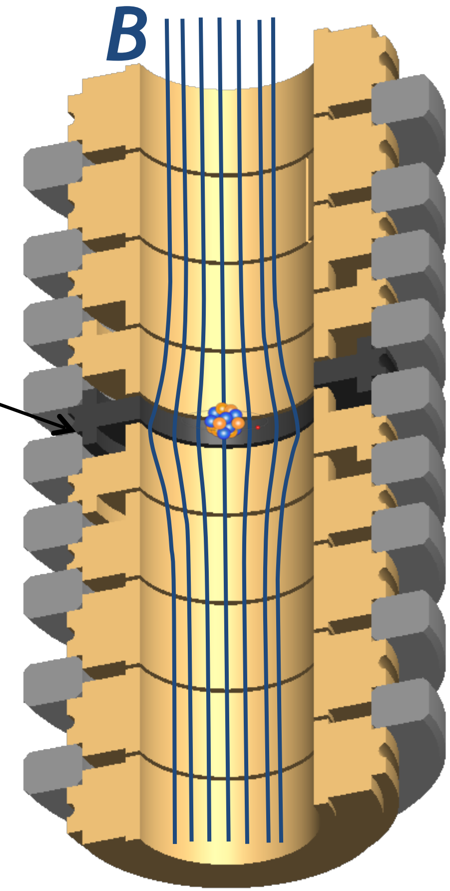

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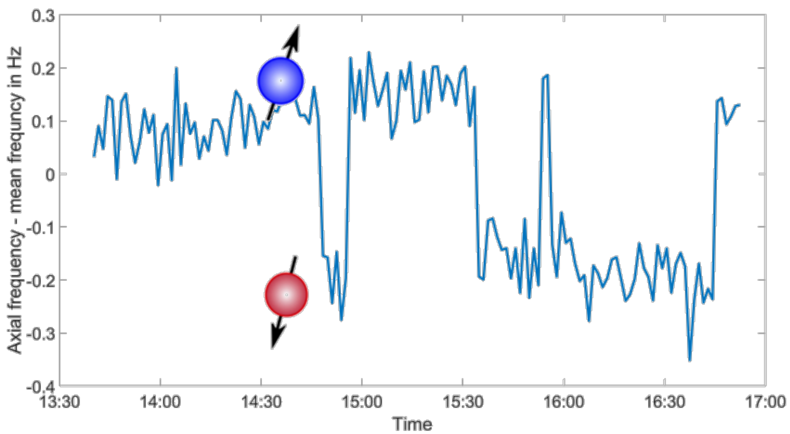

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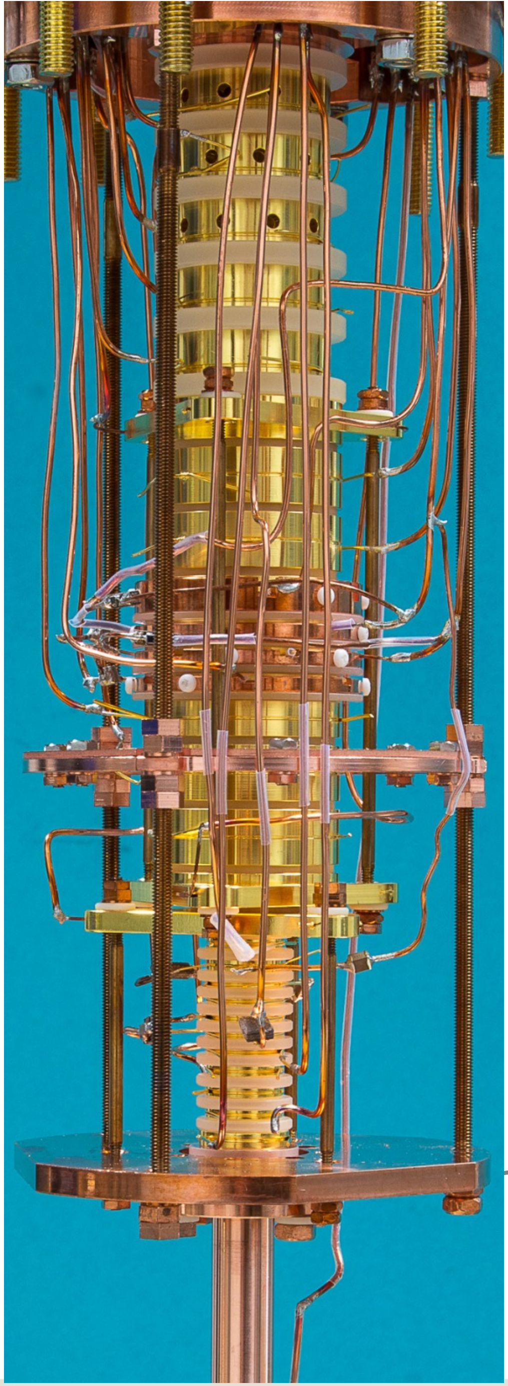
Double Penning trap

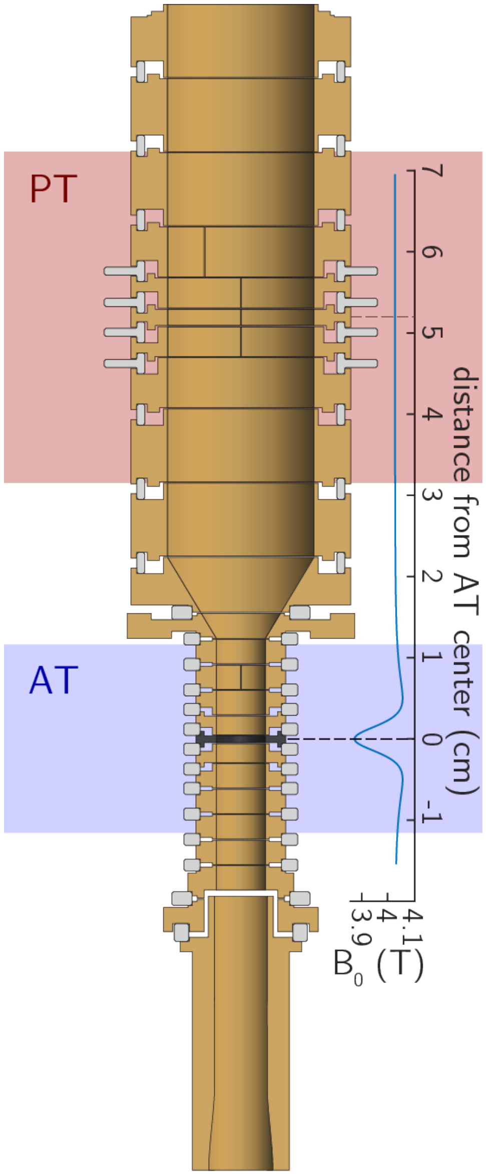


Capture electrodes
- Potential switching
- Dynamic ion capture/storage

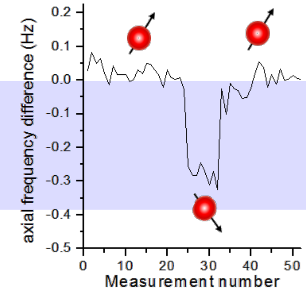
Precision trap
- 18mm diameter
- Homogeneous *B*-field: measure $\Gamma = \nu_L/\nu_c$
- Compensation ring for PT: improved *B*-field homogeneity

Analysis trap
- 6mm diameter
- Ferromagnetic ring electrode: spin detection
- B_2 ~ 44000 T/m^2

Measurement cycle



Spin state detection



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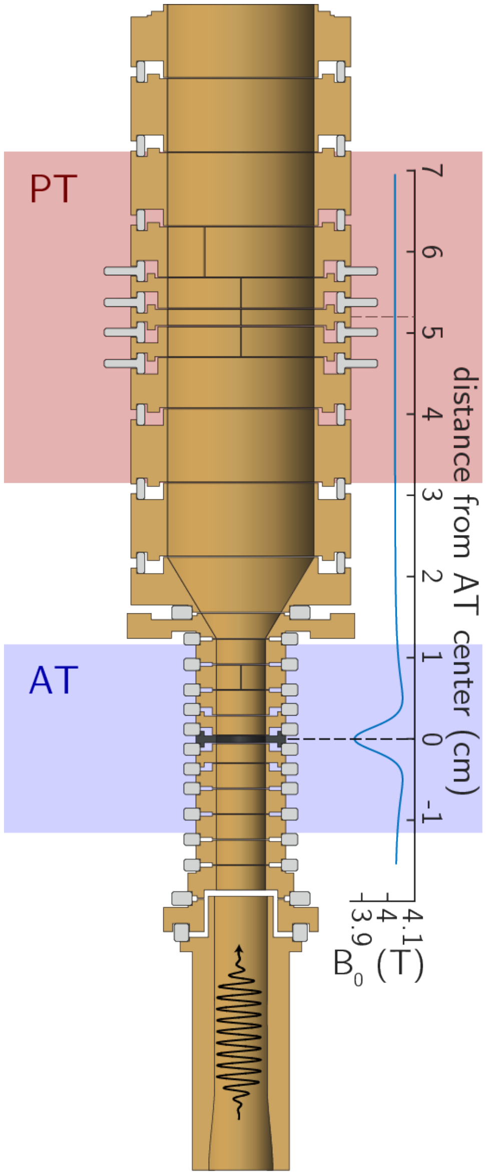

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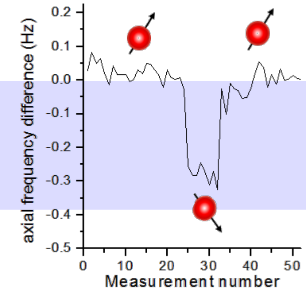
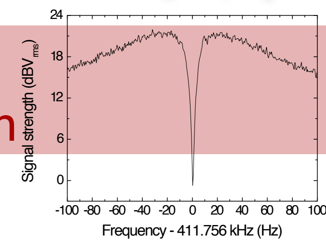


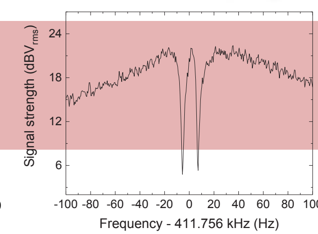
$\Gamma = \nu_L / \nu_c$ determination:

ν_c & mm-wave injection

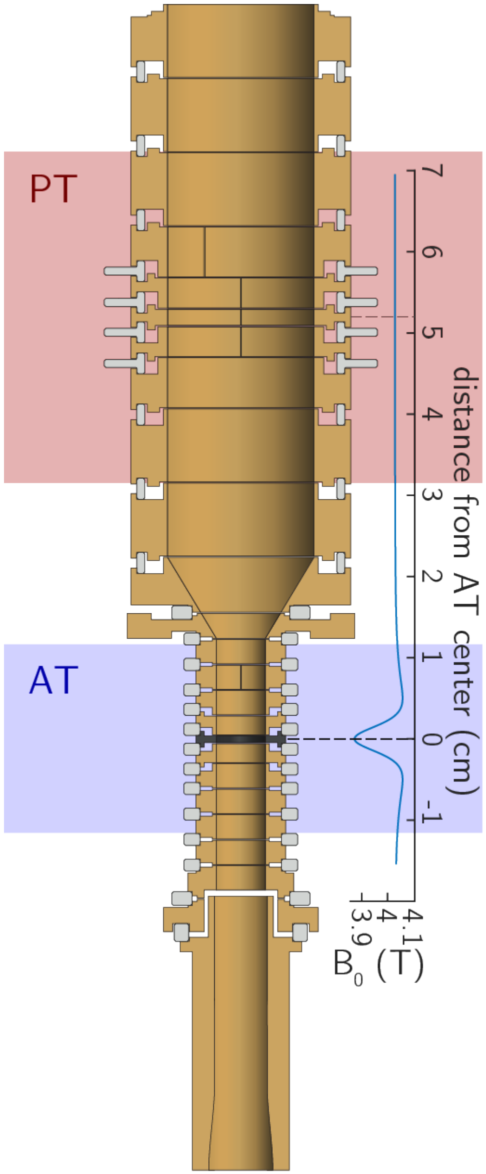
Single dip ν_z



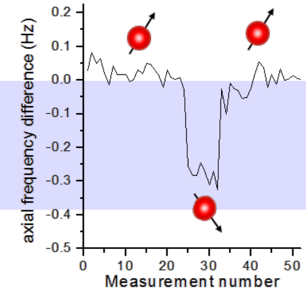
Double dip ν_+



Measurement cycle



Spin state detection



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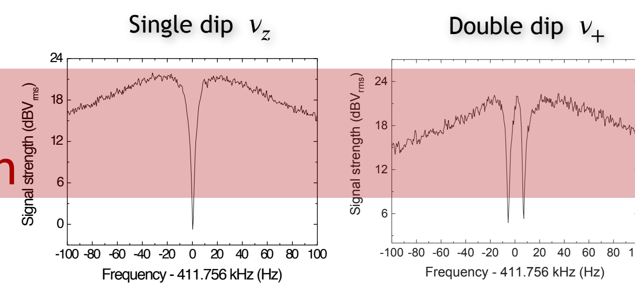
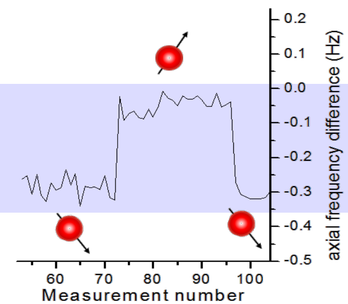
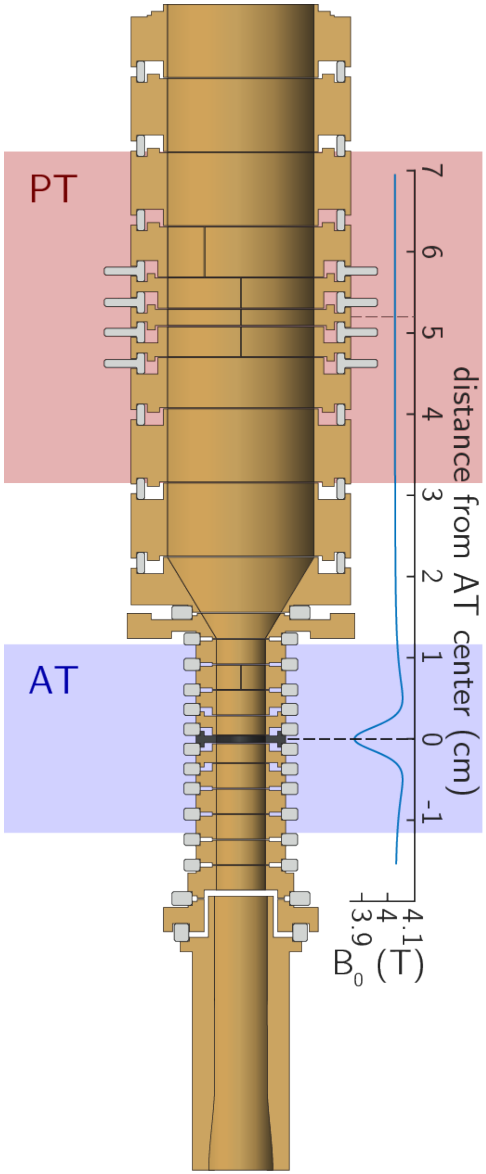


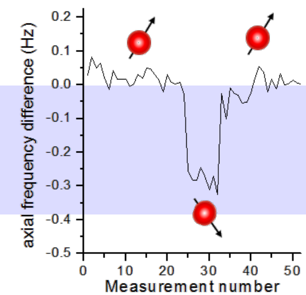
Spin state detection



Measurement cycle



Spin state detection



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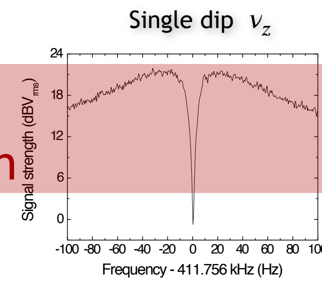
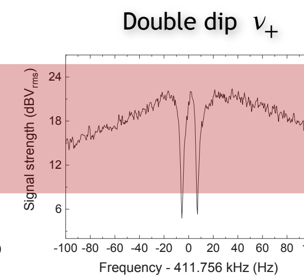
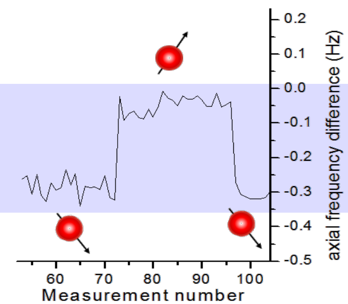
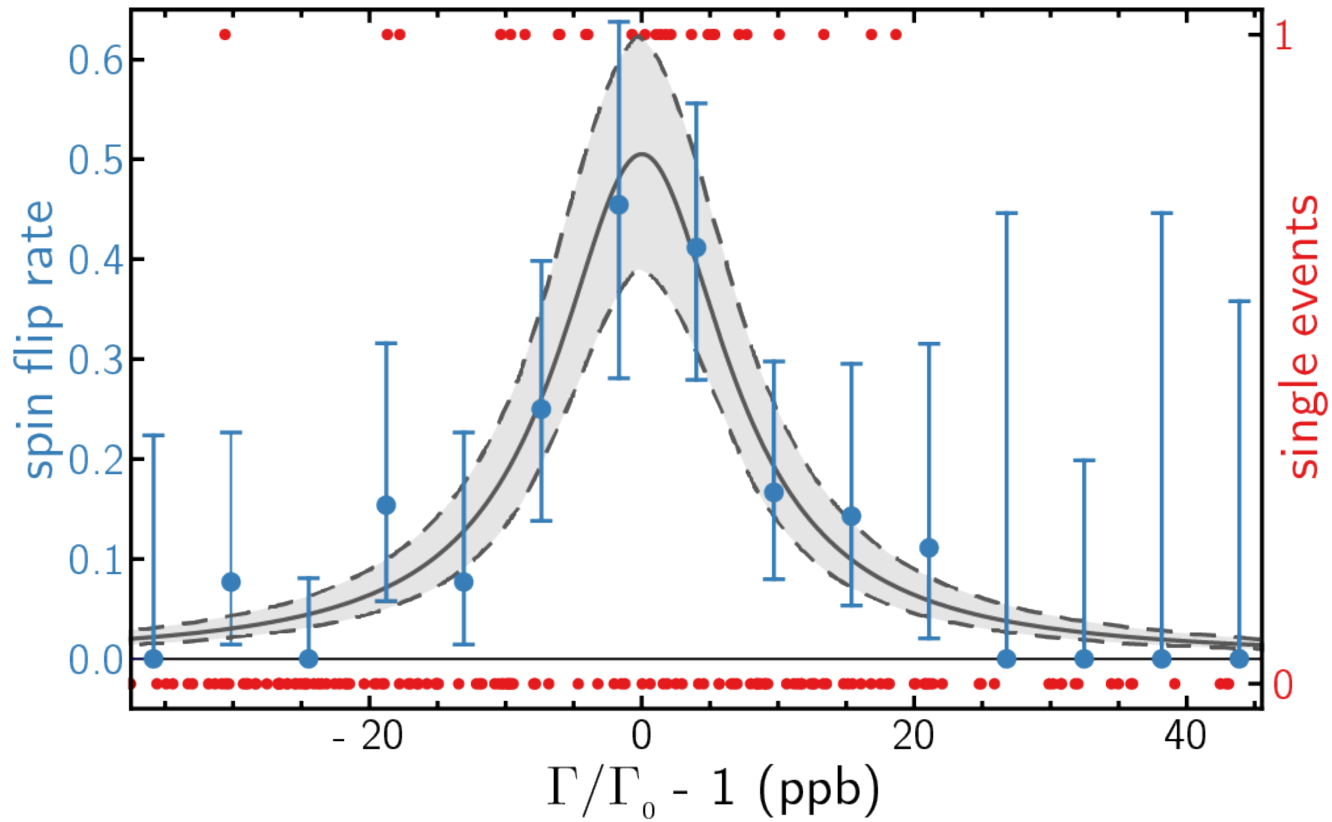




Spin state detection



g-factor of $^{40}Ar^{13+}$

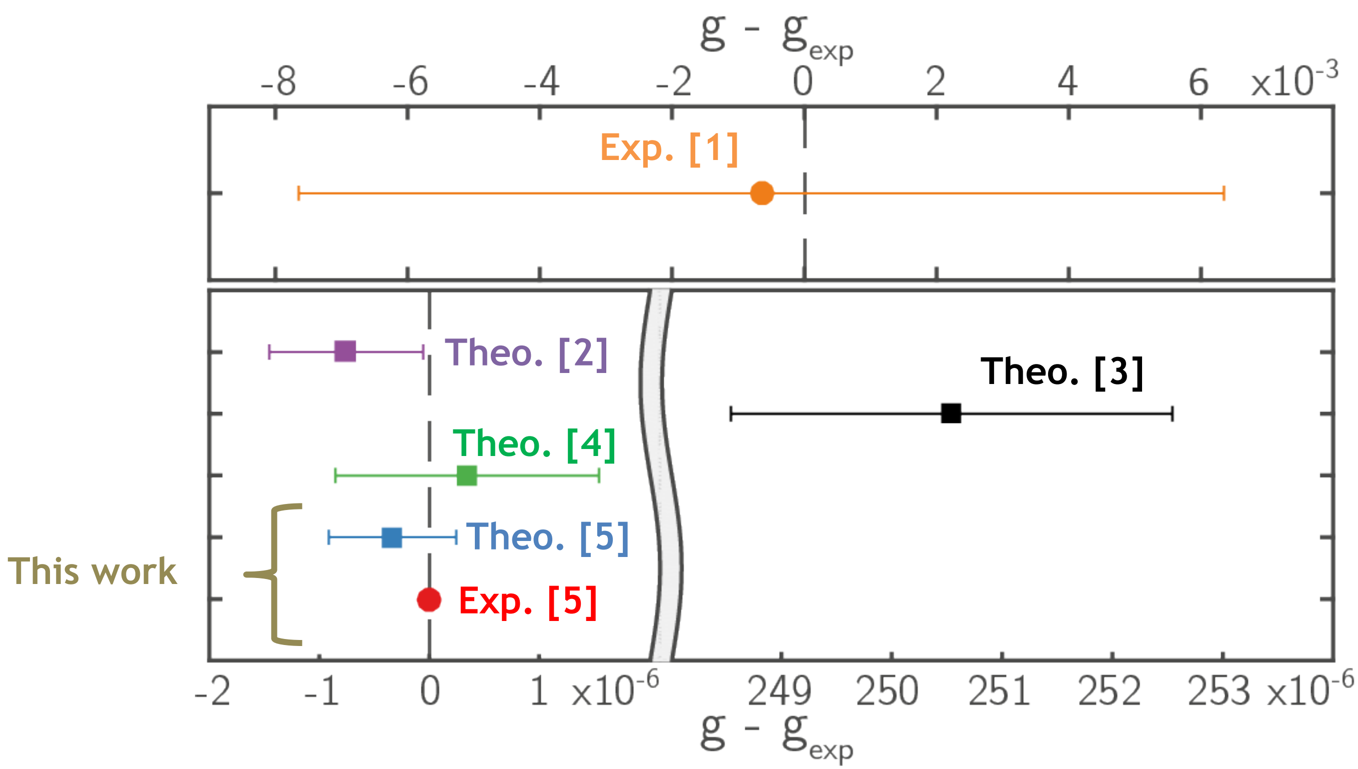


$$g = 2\Gamma_0 \frac{q_{ion}}{m_{ion}} \frac{m_e}{e}, \quad \text{where} \quad \Gamma_0 = \nu_{L0}/\nu_c$$

$$g = 0.663\,648\,455\,32\,(83)(42)(5)$$

[I. Arapoglou *et al.*, *Phys. Rev. Lett.* 122, 253001 (2019)]

Comparison with theory



Soria Orts *et al.* [1]	0.663 (7)
Shchepetnov *et al.* [2]	0.663 647 7 (7)
J. P. Marques *et al.* [3]	0.663 899 (2)
Agababaev *et al.* [4]	0.663 648 8 (12)
This work [5]	0.663 648 12 (58)
	0.663 648 455 32 (93)

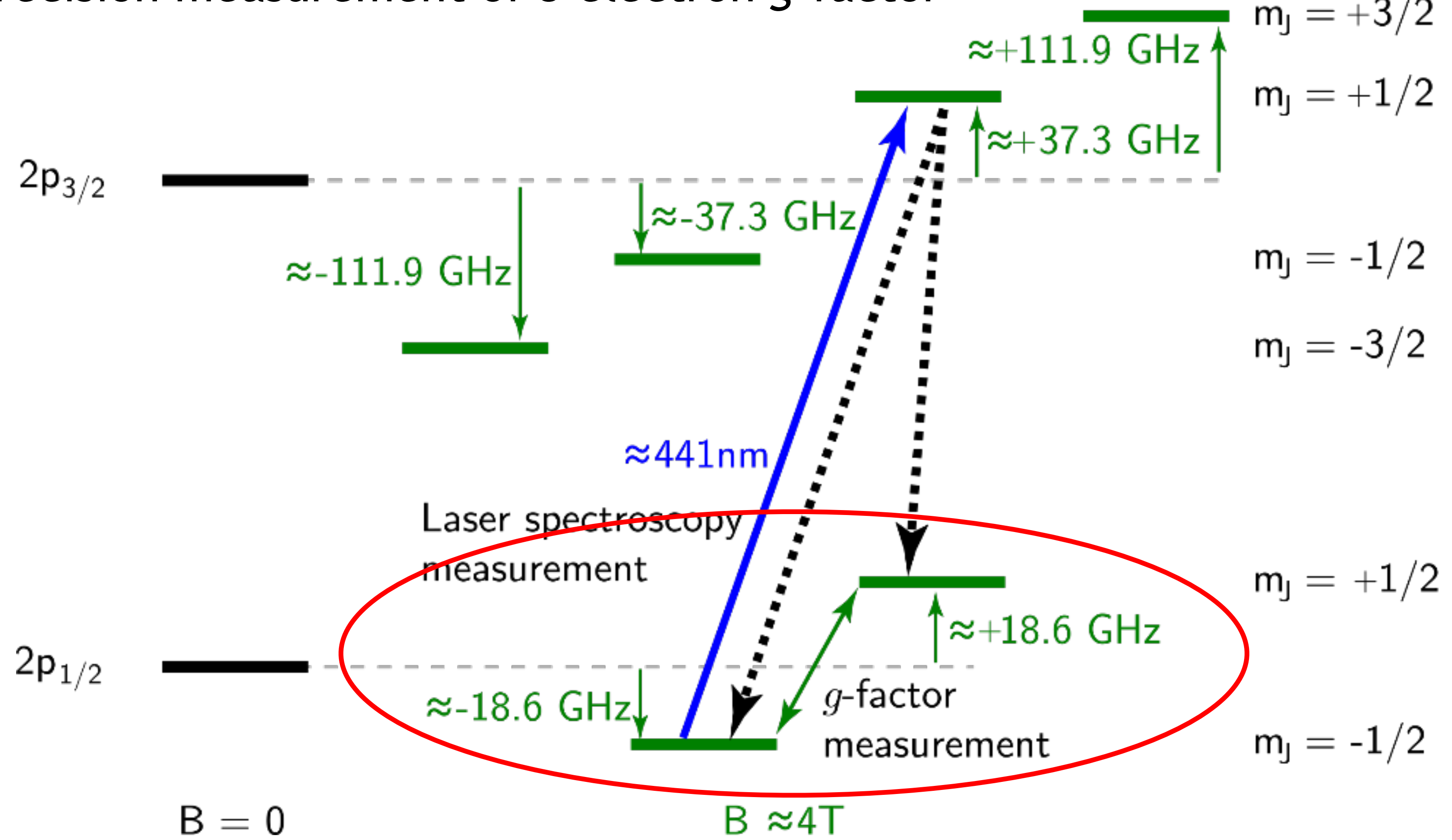
- Agreement with the current theory at 9×10^{-7} [5]
- Experimental fractional uncertainty 1.4×10^{-9}

[1] R. Soria Orts et al., *Phys. Rev. A* 76, 052501 (2007).
[2] A. A. Shchepetnov *et al.*, *J. Phys. Conf. Ser.* 583 012001 (2015).
[3] J. P. Marques *et al.*, *Phys. Rev. A* 94, 042504 (2016).
[4] V. A. Agababaev *et al.*, *J. Phys. Conf. Ser.* 1138.1(2018).
[5] I. Arapoglou *et al.*, *Phys. Rev. Lett.* 122, 253001 (2019).

Measurements so far

[I. Arapoglou *et al.*, *Phys. Rev. Lett.* 122, 253001 (2019)]

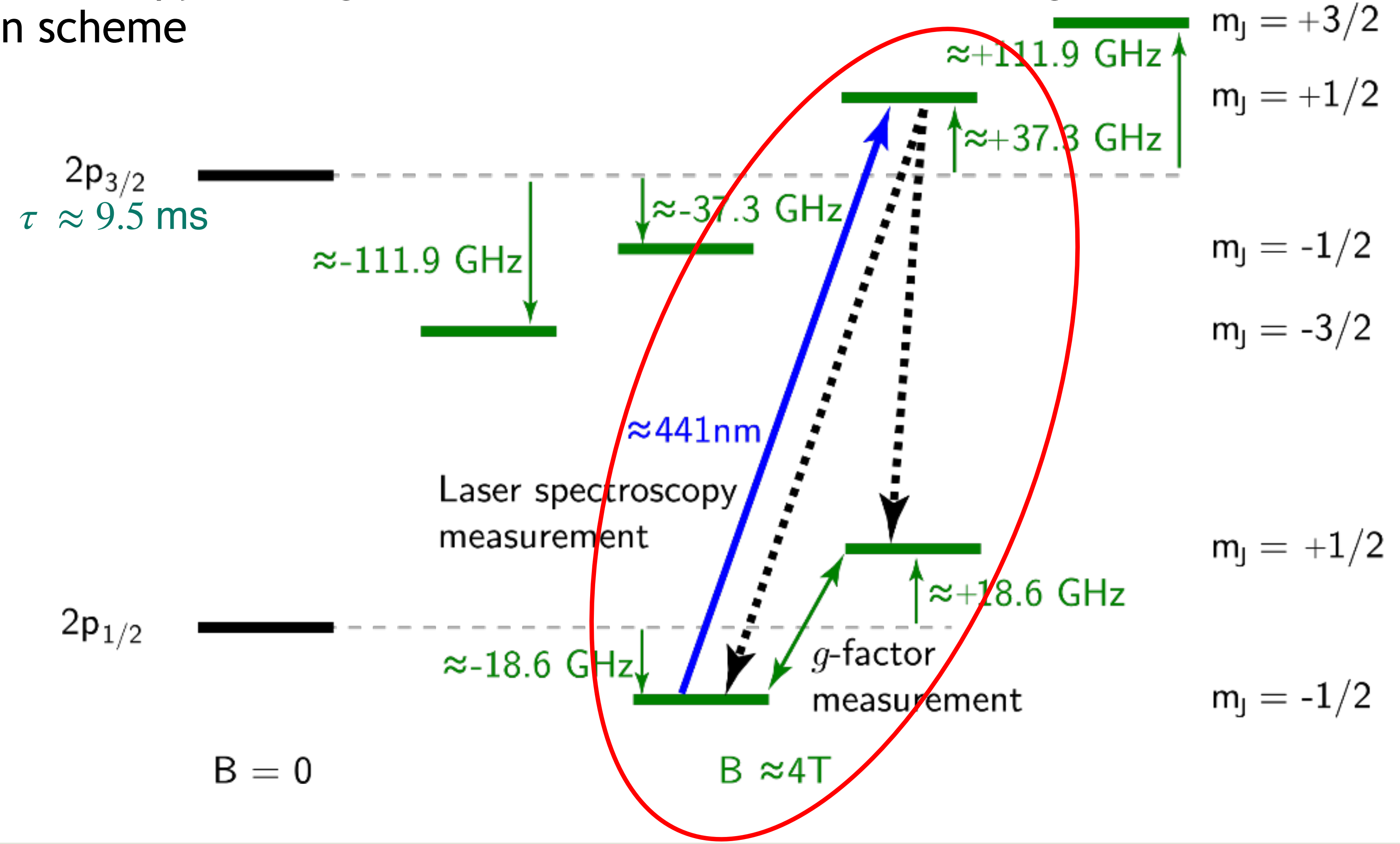
$^{40}Ar^{13+}$ measurement of *g*-factor:
first high precision measurement of 5 electron *g*-factor



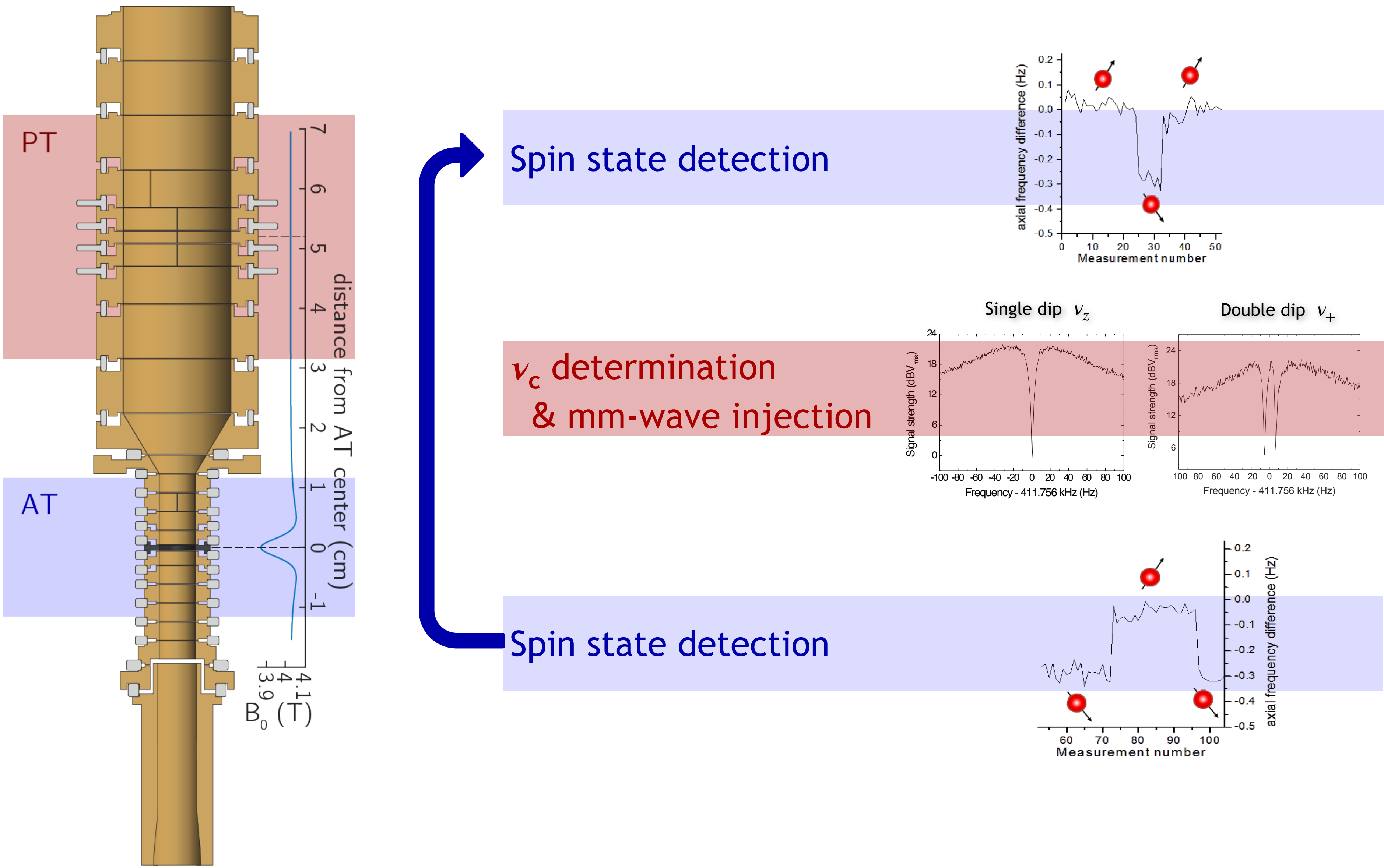
Measurements so far

[A. Egl et al. *Phys. Rev. Lett.* 123.12 (2019): 123001.]

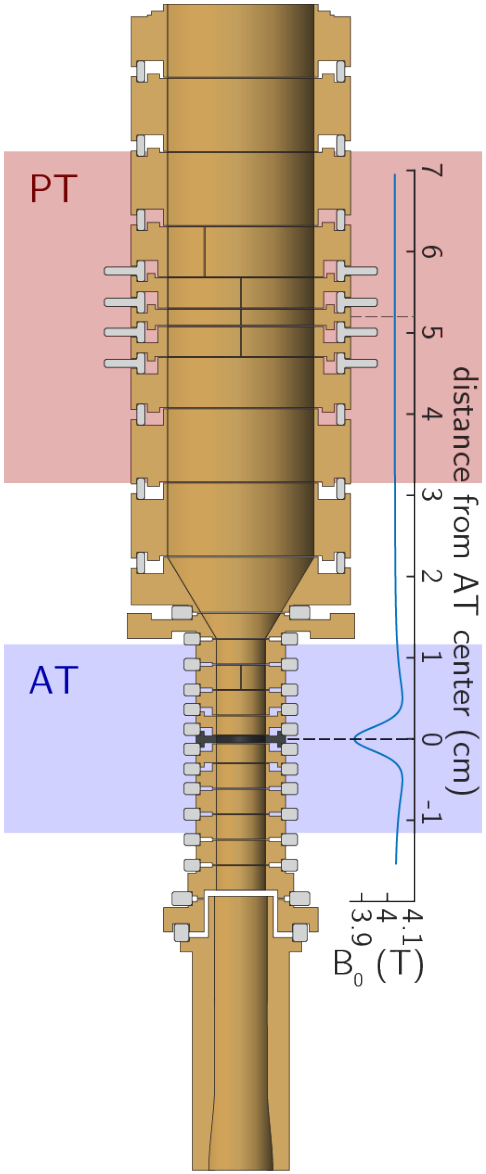
$^{40}Ar^{13+}$ measurement of the fine-structure transition:
laser spectroscopy on magnetic fine-structure transition using a novel detection scheme



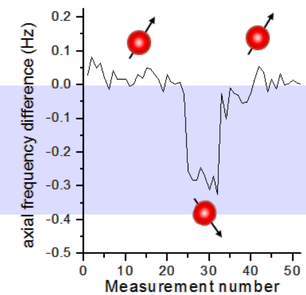
Measurement cycle



Measurement cycle



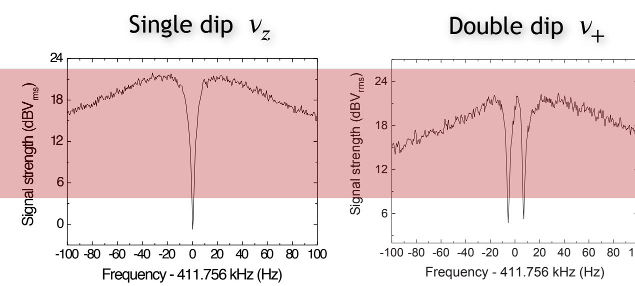
Spin state detection



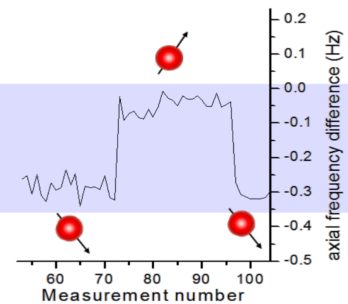
ν_c determination

& ~~mm wave injection~~

laser injection



Spin state detection



Results

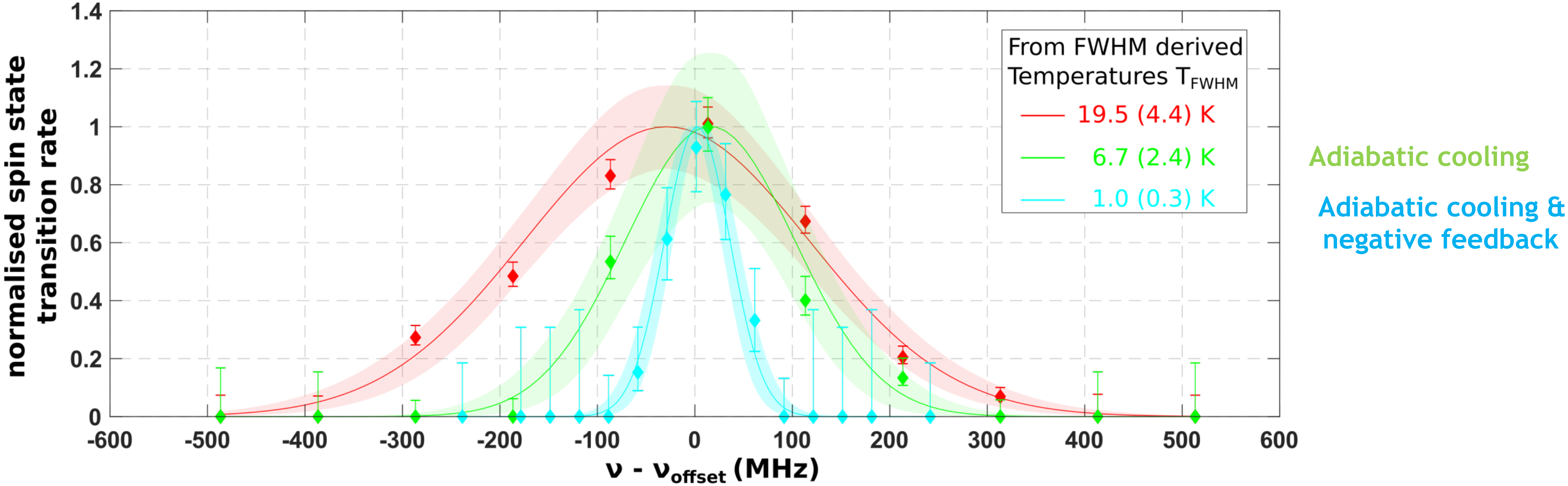
The precision of the transition frequency measurement is limited by

- Resonance width (Ion temperature dominant)
- Laser frequency stability and absolute frequency calibration

Improvement of the precision

➢Sympathetic laser cooling
➢Resolving the individual motional sidebands via a more stable laser frequency

$\nu = 679.216464(4)_{stat}(5)_{syst}$ THz   Improved by a factor of 24



[A. Egl et al. *Phys. Rev. Lett.* 123.12 (2019): 123001.]

Summary and Outlook

★ First measurements of the ALPHATRAP experiment

★ First high-precision measurement of boronlike HCI g-factor
  - towards α determination

★ Fine structure spectroscopy without fluorescence detection

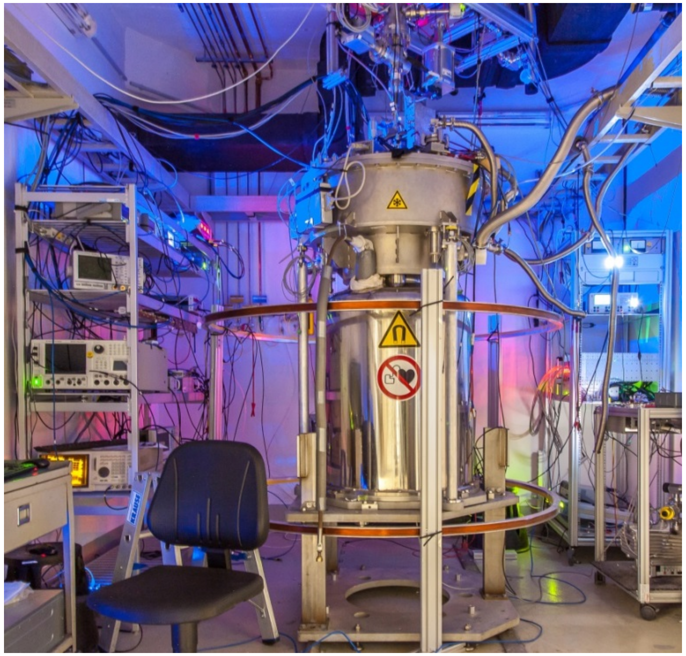
➢ Isotope shift measurement and QED effect in the nuclear recoil
  ($^{40}Ca^{19+}$ and $^{48}Ca^{19+}$)

➢ Sympathetic laser cooling
  - Higher precision
  - Coulomb crystalization

➢ g-factor measurements of highly charged high-Z ions
  - Testing QED in strong fields
  - α determination

The ALPHATRAP team: Klaus Blaum, Sven Sturm, Bingsheng Tu, Andreas Weigel, Ioanna Arapoglou, Alexander Egl, Tim Sailer, Felix Heine and ...

Thank you for your attention!



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