Observation of metastable electronic states in highly charged ions at Pentatrap

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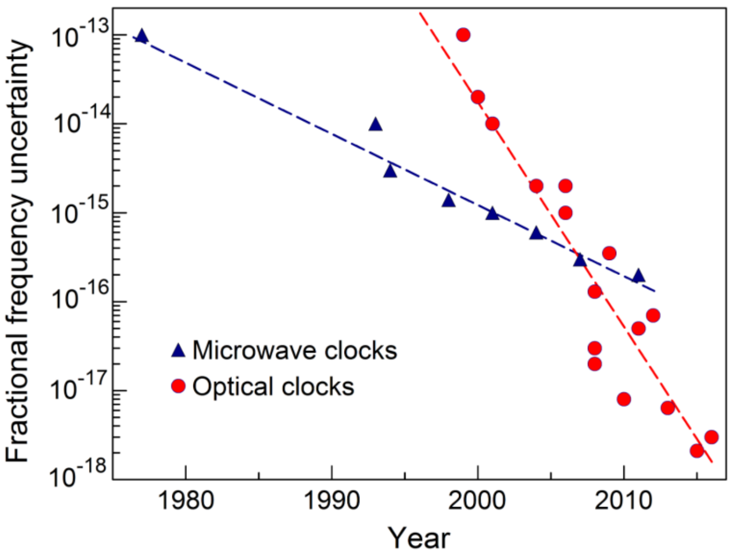
Motivation

- Atomic clocks have a lot of applications e.g. geodesy, GPS, metrology etc.
- Research into physics beyond the standard model
  - Variation of fundamental constants e.g. the fine structure constant α



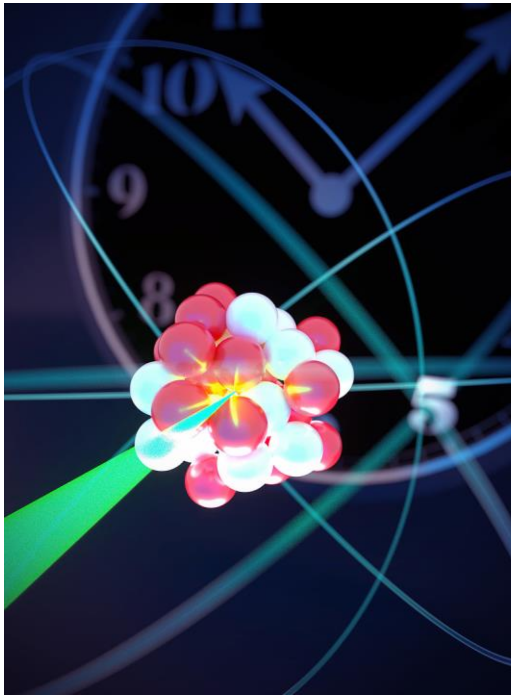
Safronova *et al.,* Rev. Mod. Phys. **90**, 025008 (2018)

- Optical clocks have reached incredible precision
- What could surpass that?
  - Theory proposes transitions in highly charged ions
    - ➢ Enhanced sensitivity to α
  - Advancements in frequency combs make XUV spectroscopy possible

Ingredients for a highly charged ion (HCI) clock

- Find suitable clock transition
  - Among other things: XUV transition energy, long lifetime
- Figure out cooling and state readout of the HCI
  - Quantum logic method

  King *et al.*, Nature **611** 43-47 (2022)
- Prepare a highly charged ion
  - Electron Beam Ion Trap (EBIT)
- Figure out a laser system in resonance with the transition frequency



Picture credit: PTB

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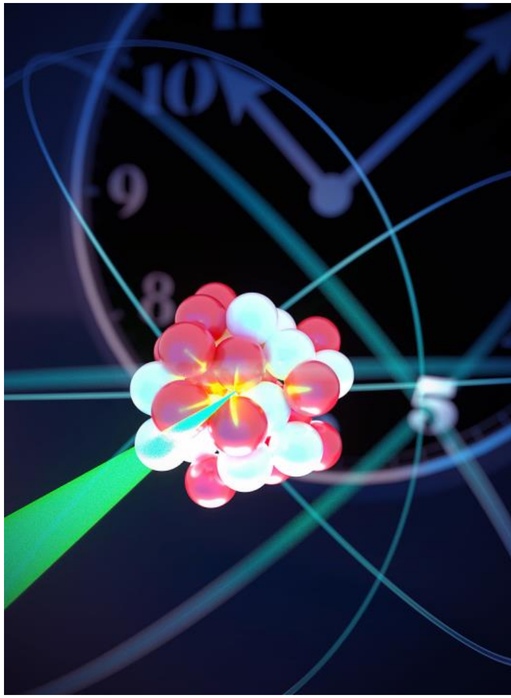
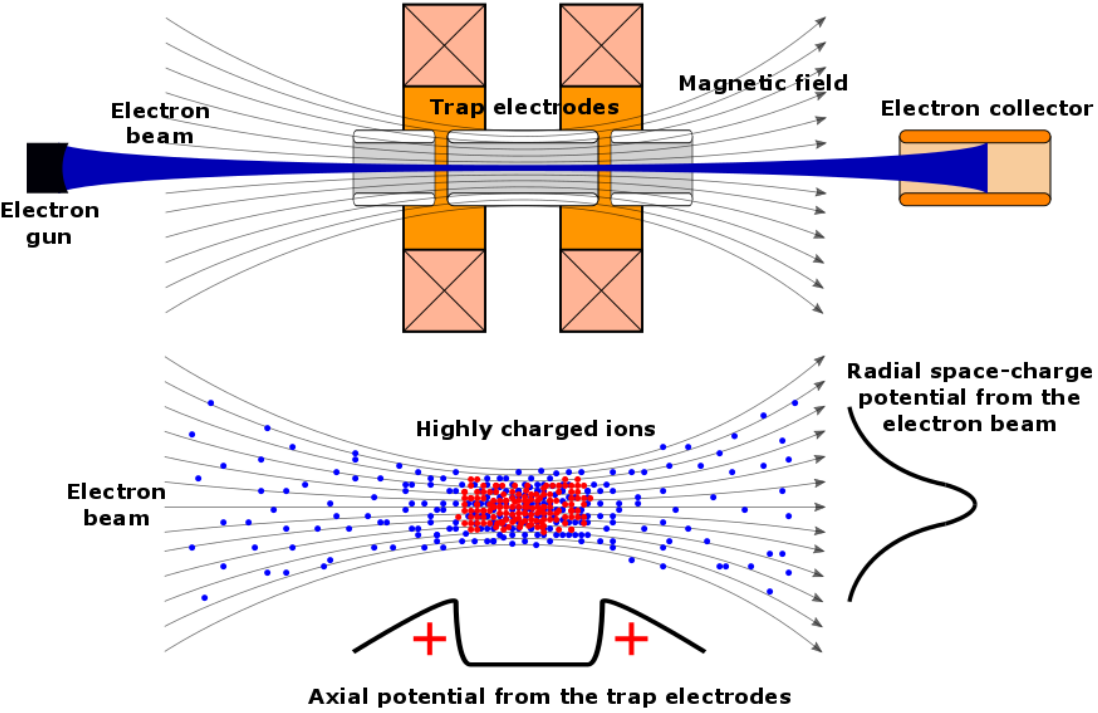
→ We could determine the transition energy beforehand and test if theoretical atomic structure calculations are correct.

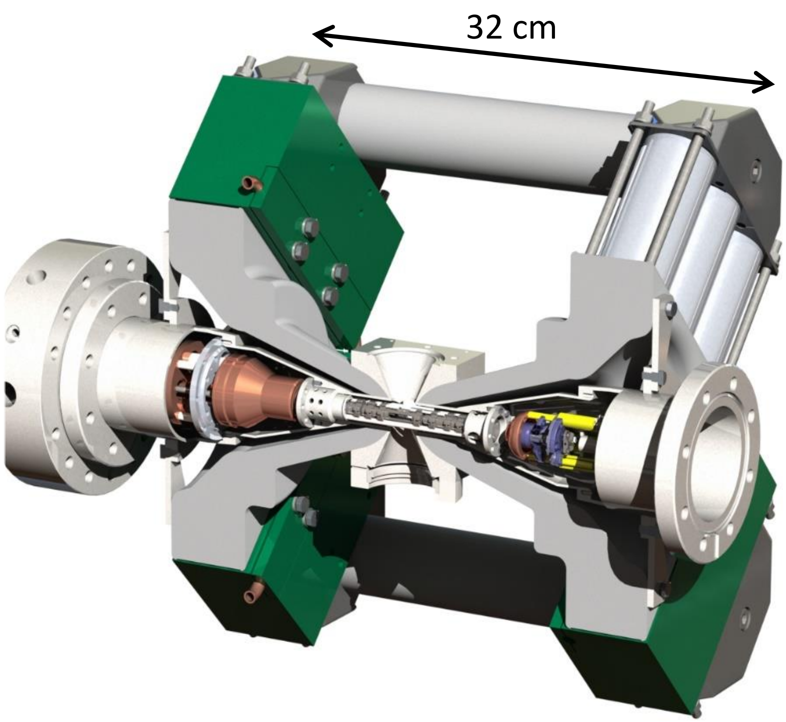


Picture credit: PTB

Heidelberg compact EBITs

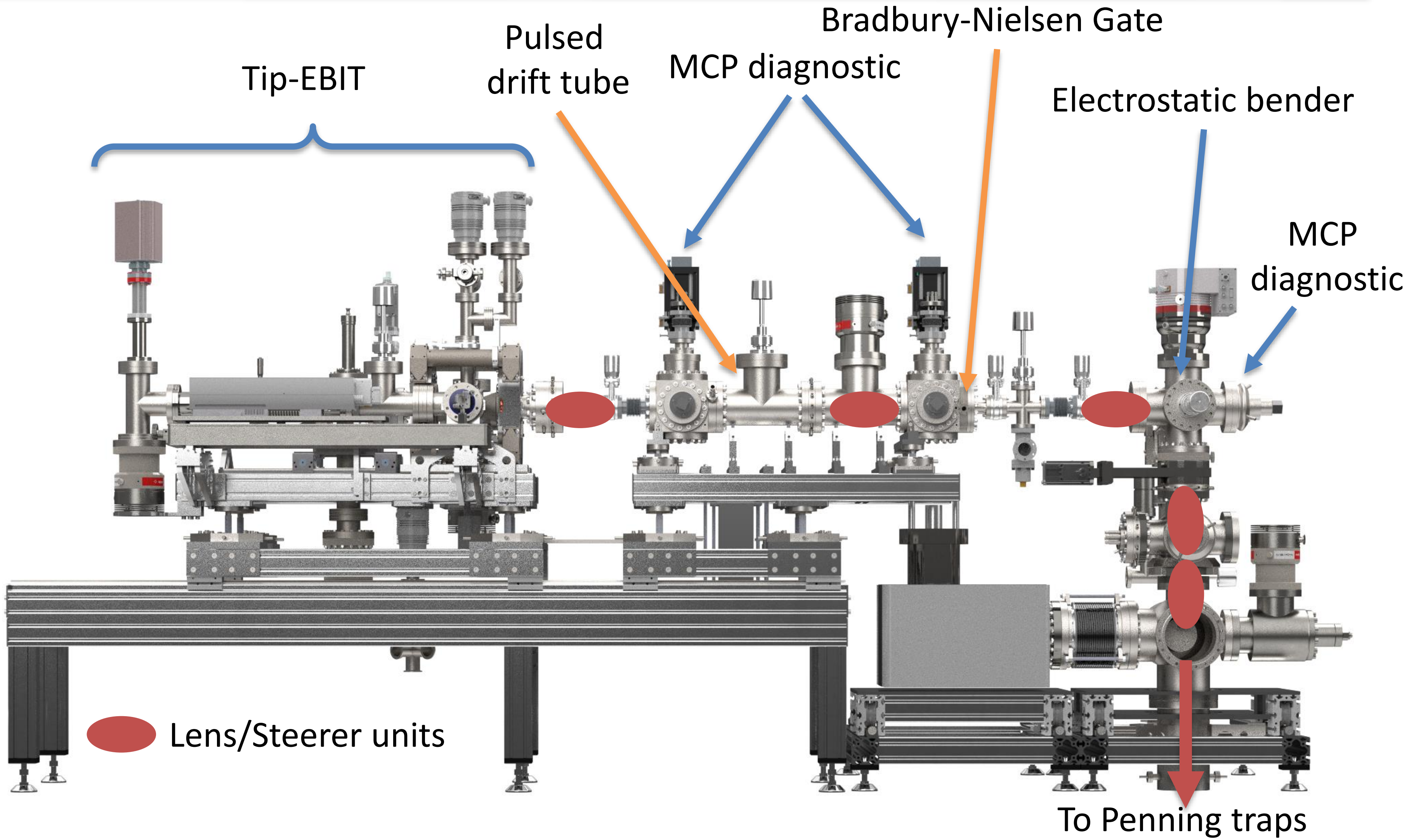


72 NdFeB permanent magnets



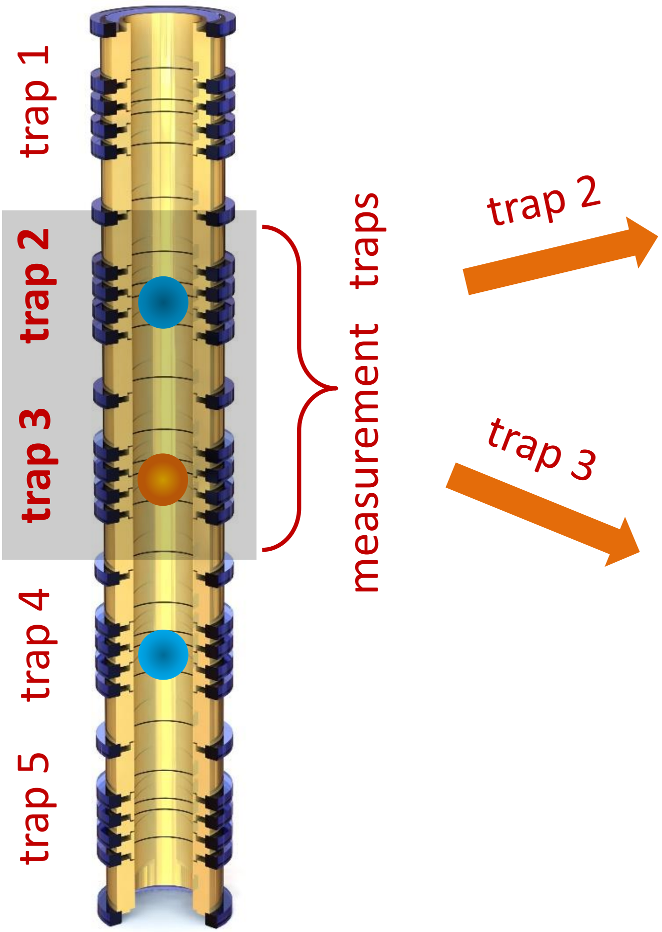
Micke, P. et al., Rev. Sci. Instr. 89, 063109 (2018)

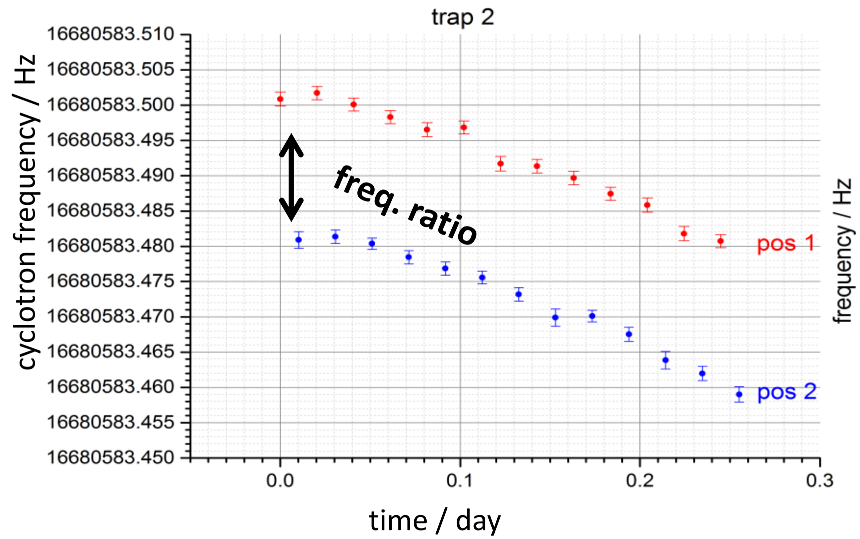
Tip-EBIT beamline

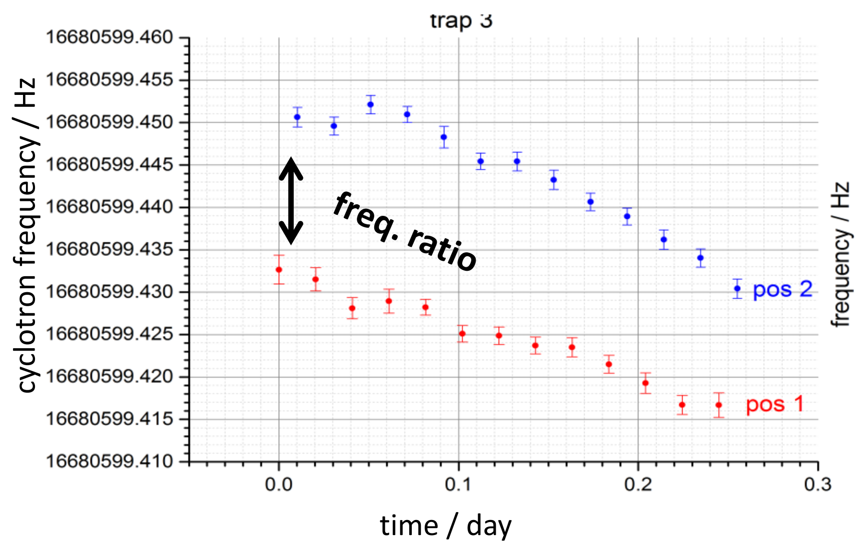


Measurement preparation and procedure

Position 1/2







Metastable state in $^{187}\mathrm{Re}^{29+}$ and $^{187}\mathrm{Os}^{30+}$

Experimental energy difference:

$$\Delta E = 202.2(1.7)\ \mathrm{eV}$$

Theory Quanty: M. Haverkort

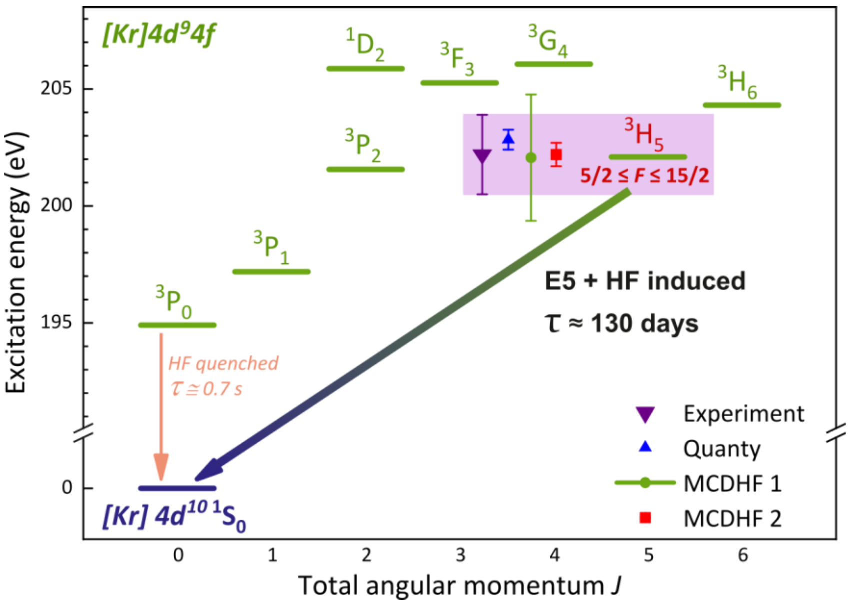
$$\Delta E = 202.8(4)\ \mathrm{eV}$$

Theory MCDHF1: P. Indelicato

$$\Delta E = 202.2(1.6)\ \mathrm{eV}$$

Theory MCDHF2: Z. Harman

$$\Delta E = 202.2(5)\ \mathrm{eV}$$



Schüssler *et al.*, Nature **581**, 42-46 (2020)

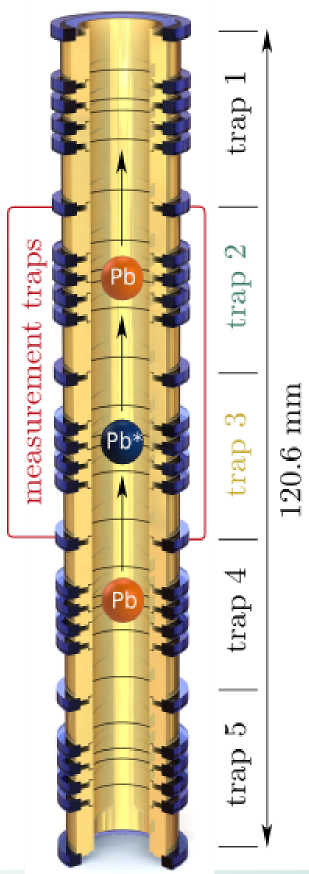
Metastable electronic state in $^{208}\mathrm{Pb}^{41+}$

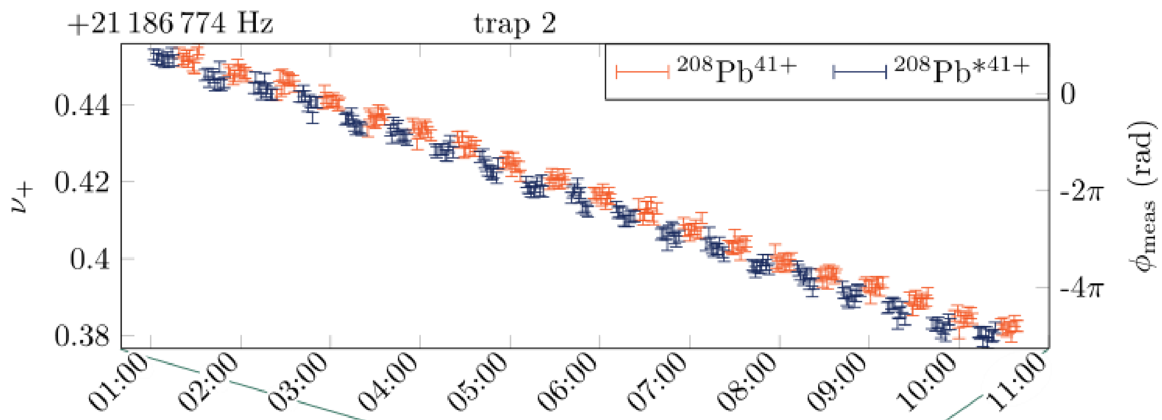
$$\omega_-^{\text{ground}} = \omega_-^{\text{metastable}}$$

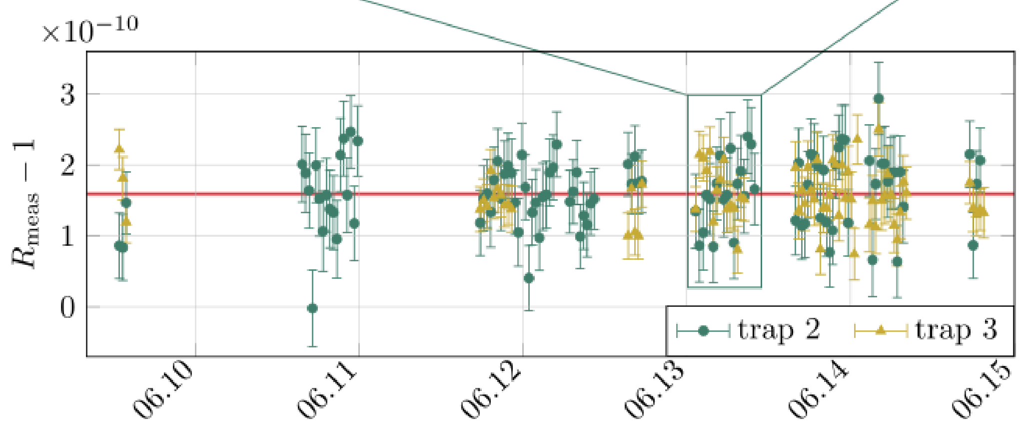
$$\omega_z^{\text{ground}} = \omega_z^{\text{metastable}}$$

$$\omega_+^{\text{ground}} = \omega_+^{\text{metastable}} + 4\ \text{mHz}$$

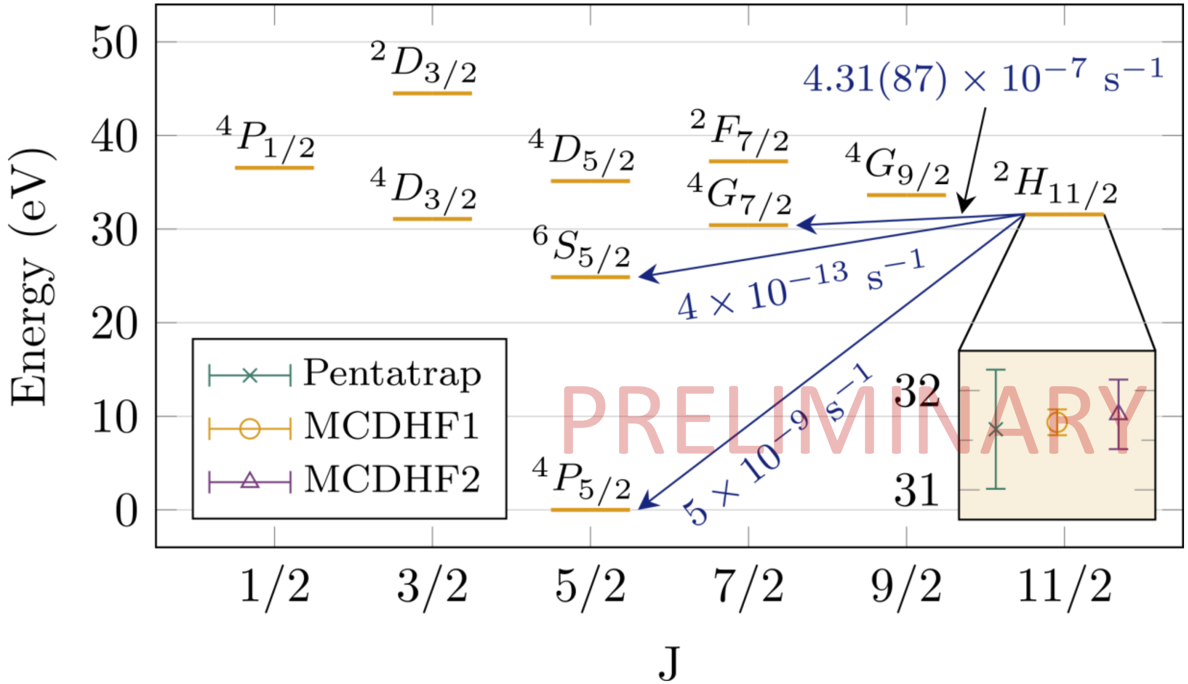
Identification only possible if 2 ions are present!







Comparison to theory



Experimental ratio precision of $3 \cdot 10^{-12}$ 31.X ± 0.6eV

MCDHF1: Zoltán Harman/ Chunhai Lyu @ MPIK Heidelberg
MCDHF2: Paul Indelicato @ CNRS Paris

Metastable states measurement outlook

Table 1. Summary of metastable state in highly charged ions.

isoelectron	ion	metastable state	energy (eV)	lifetime
23V-like	U^{69+}	$[Ar]3d^5\ ^2H_{11/2}$	197.0	12.6 hours
23V-like	Th^{67+}	$[Ar]3d^5\ ^2H_{11/2}$	176.3	25.3 hours
41Nb-like	U^{51+}	$[Kr]4d^5\ ^2H_{11/2}$	57.5	8.3 days
22Ti-like	U^{70+}	$[Ar]3d^4\ ^3H_4$	205.9	46.3 days
22Ti-like	Xe^{32+}	$[Ar]3d^4\ ^5D_4$	17.9	3.0 hours
22Ti-like	Ba^{34+}	$[Ar]3d^4\ ^5D_4$	21.1	10.3 hours
22Ti-like	Ce^{36+}	$[Ar]3d^4\ ^5D_4$	24.8	54.5 hours
40Zr-like	U^{52+}	$[Kr]4d^5\ ^2H_{11/2}$	59.8	10.9 years
40Zr-like	Gd^{24+}	$[Kr]3d^4\ ^5D_4$	9.0	5.3 hours
40Zr-like	Dy^{26+}	$[Kr]3d^4\ ^3F_4$	10.6	16.3 hours

Table calculated by Chunhai Lyu (group Zoltán Harman from the MPIK Heidelberg)

next goal:

Xe^{32+}, Ba^{34+}

Summary and outlook

Finished Measurements:

- Statistical uncertainty of $3 * 10^{-12}$ shown with PENTATRAP
- Detection of an electronic metastable state in Pb
- Yb isotope chain (Menno)

Ongoing measurement and future plan:

- Currently measuring Ca isotope chain for fifth force search
- He-4 mass determination for light ion puzzle
- Rb/Cs mass for alpha determination

Thanks to

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FOR 2202

ECHo

DFG Research Unit
FOR 2202

isoQuant
SFB1225

Project-ID 273811115

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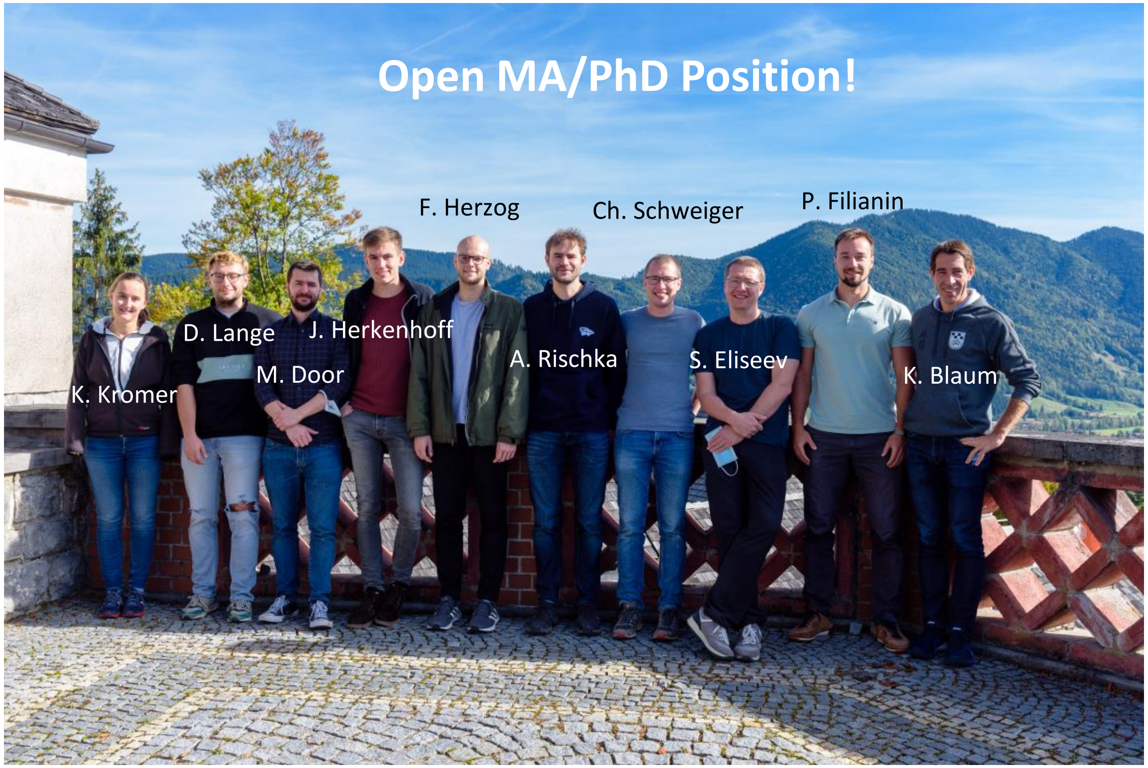

Experiment: José R. Crespo López-Urrutia, Menno Door, Pavel Filianin, Jost Herkenhoff, Daniel Lange, Christoph Schweiger, Sergey Eliseev, Klaus Blaum

Theory: Zoltán Harman, Paul Indelicato, Christoph H. Keitel, Chunhai Lyu

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PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

and you, for your attention!

Rhenium: Discovery of metastable states in HCIs

Little trip down memory lane: β −decay in Re:

$$\underbrace{{}^{187}\mathrm{Re} \rightarrow \quad {}^{187}\mathrm{Os}}_{\text{Mass difference measurement}} + \tilde{\nu}_e + e^-$$

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

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

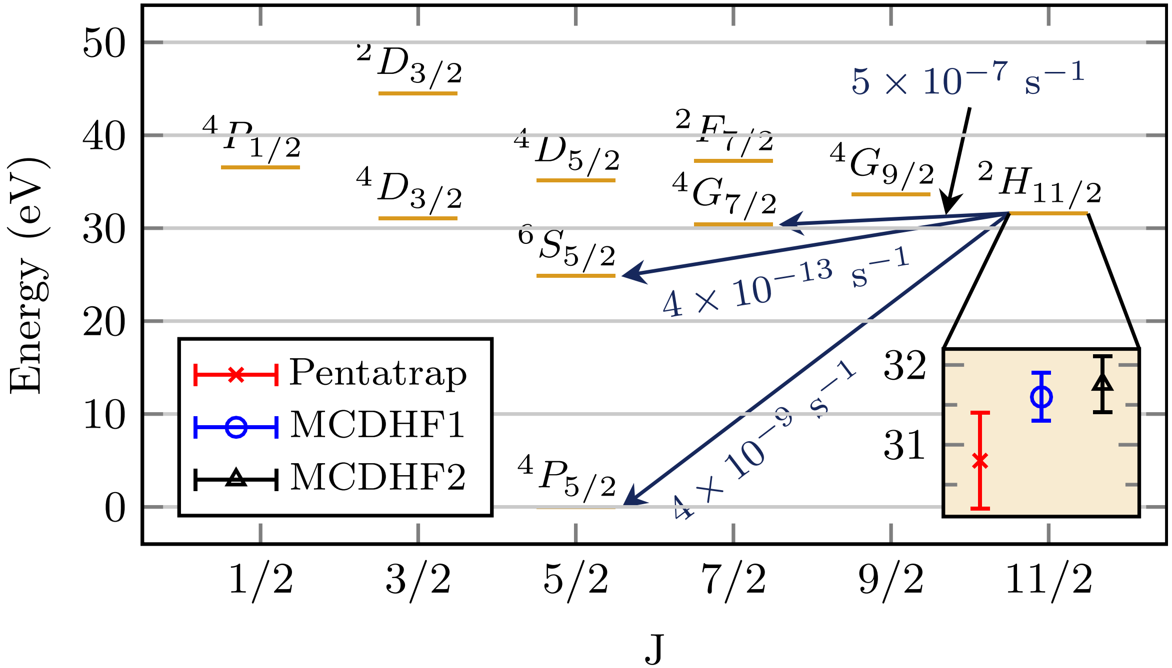
R_1 = 1.000000013886(15)
R_2 = 1.000000015024(12)

- Os^{29+} vs. Os^{29+}: $R = 1$
- Re^{29+} vs. Re^{29+}: $R = 1$ or $R = 1 + 1.16 \cdot 10^{-9}$

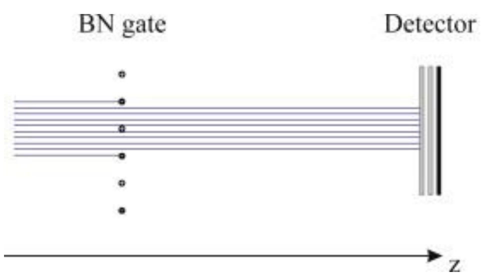
Ions can be produced in metastable electronic configurations!

Backup slides

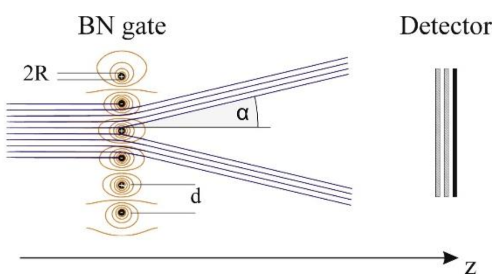
- The metastable [Kr]4d^5 ^2H_{11/2} lies at around 31eV above the [Kr]4d^5 ^4P_{5/2}. It decays mainly via an E2 transition to the short-lived state [Kr]4d^5 ^4G_{7/2}. The metastable state has a lifetime of around 23days.



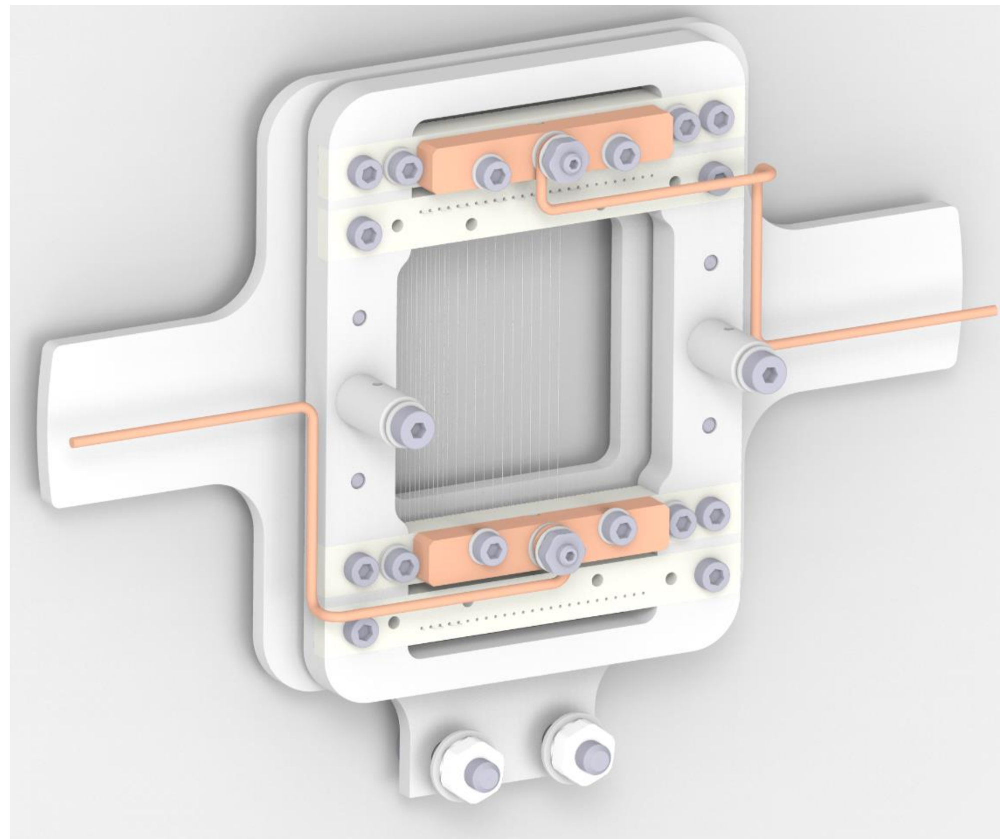
Bradbury-Nielsen Gate



NO voltage applied



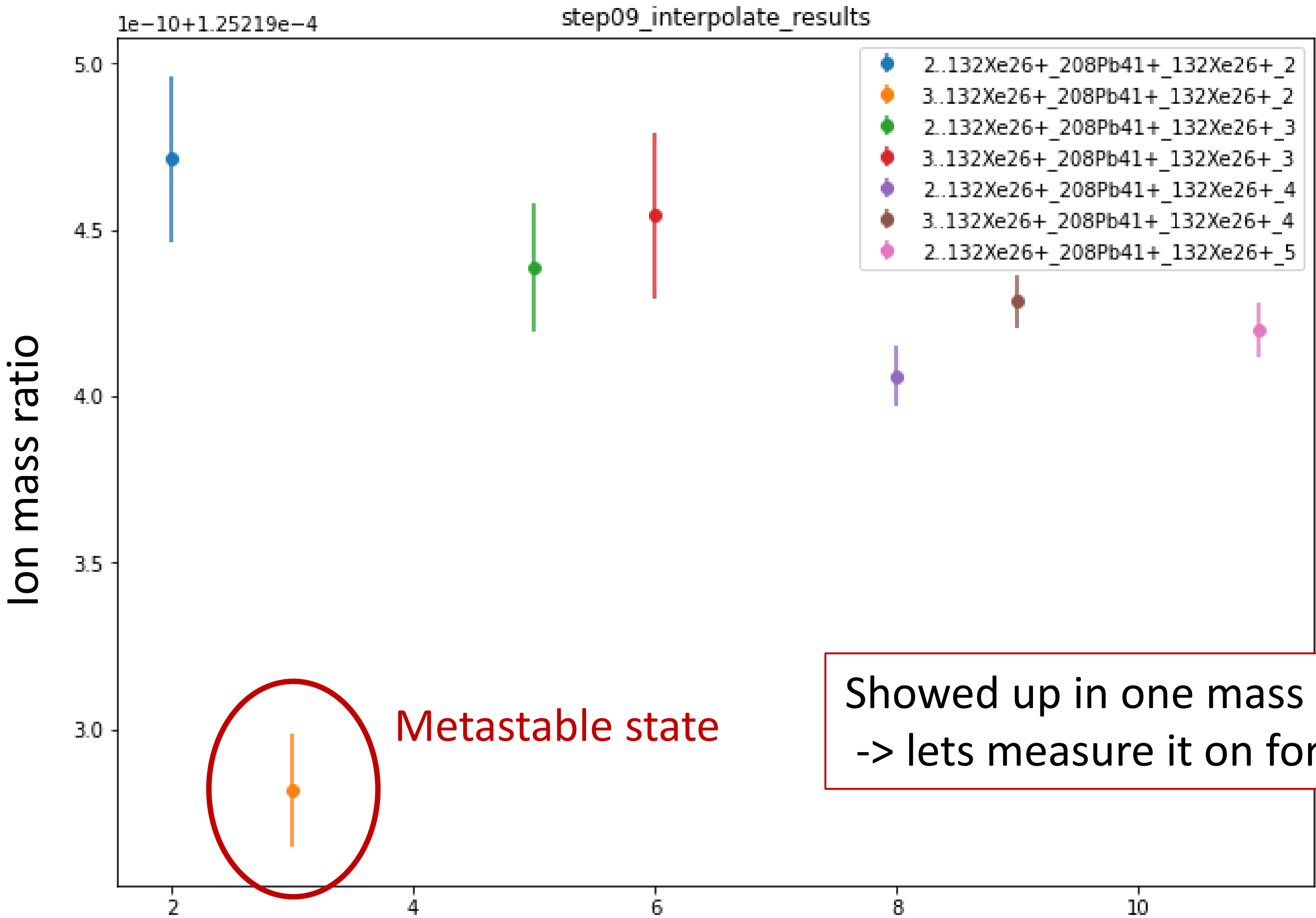
POS/NEG voltage applied



Wolf, R.N. et al., *NIMA 686, 82* (2012)
Brunner, T. et al., *IJMS 309*, 97 (2012)

Metastable state in Pb^{41+}

- FAC calculation: 30.9 eV above ground state



Showed up in one mass measurement
-> lets measure it on for real