MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Investigating α time variation with cold highly charged ions

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Experimental Few-Particle Quantum Dynamics

The collaboration

Highly charged ions

Electron beam ion traps (EBITs)

EBIT spectroscopy

DEPARTMENT OF PHYSICS
AND ASTRONOMY
FACULTY OF SCIENCE
AARHUS UNIVERSITY

Coulomb crystals

Linear Paul trap design

Molecular ions

Quantum logic readout

High-accuracy clocks

Frequency comb

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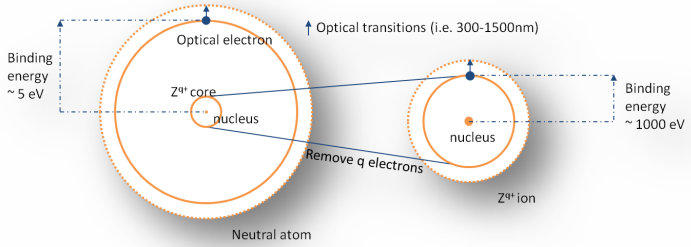
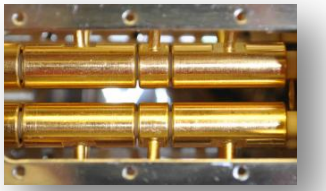
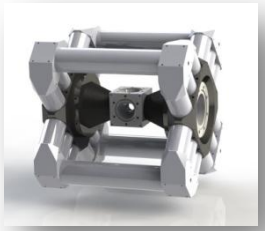
Overview

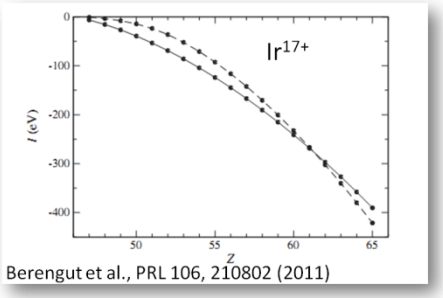


- Highly charged ions for metrology and fundamental physics
- Cryogenic Paul trap for sympathetic cooling of HCIs



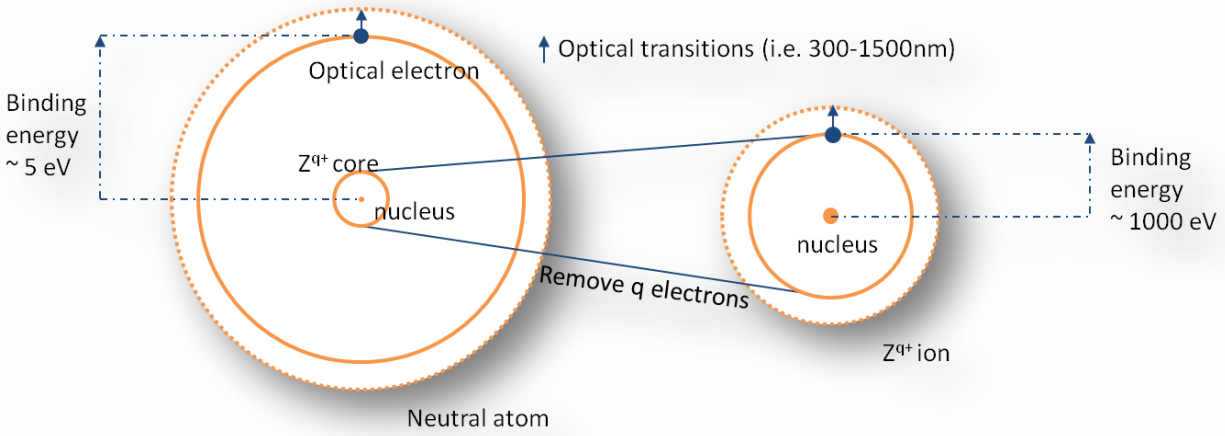
- Ir^{17+} and time variation of fine structure constant
- Outlook





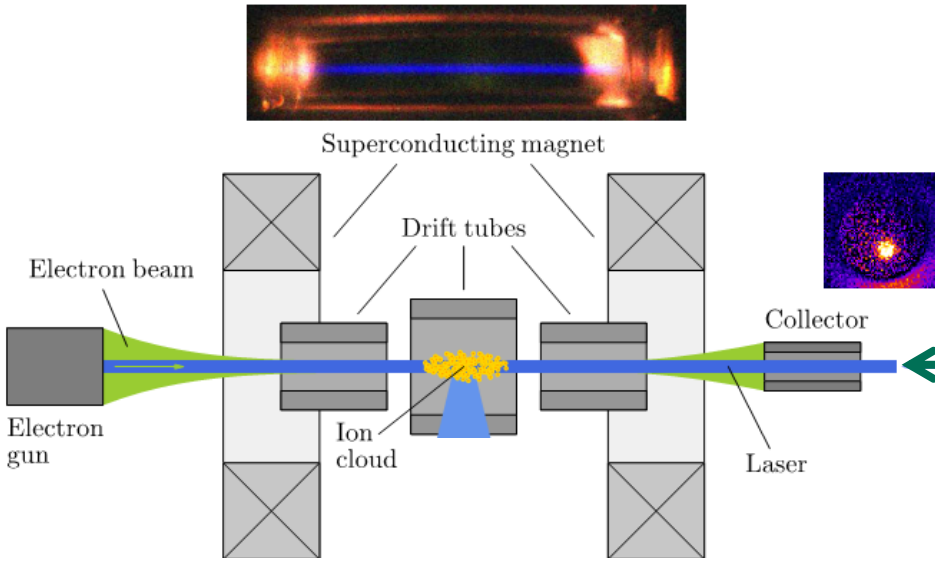
Berengut et al., PRL 106, 210802 (2011)

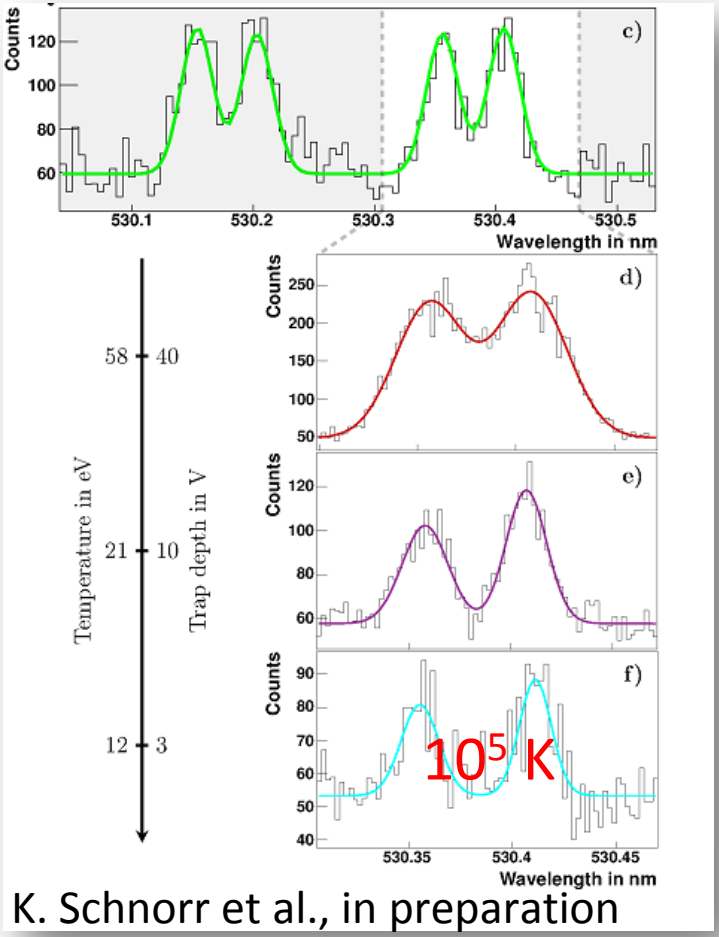
Highly charged ions, scaling laws



- Ionization energy ~ Z^2
- Fine structure ~ Z^4
- Bohr radius ~ Z^{-1}; electron density at nucleus ~ Z^3
- Weak matrix element (parity violation) ~ Z^5
- QED contributions ~ $(Z\alpha)^n$

Laser spectroscopy of HCIs





K. Schnorr et al., in preparation

Ar^{13+} $^2P_{3/2}$–$^2P_{1/2}$ @ 441 nm by pulsed dye laser

Evaporatively cooled from 240 to 28eV (12eV achieved!)

Limited by Doppler line width! Need cooling…

Sympathetic Cooling of HCIs

- RETRAP (LLNL):

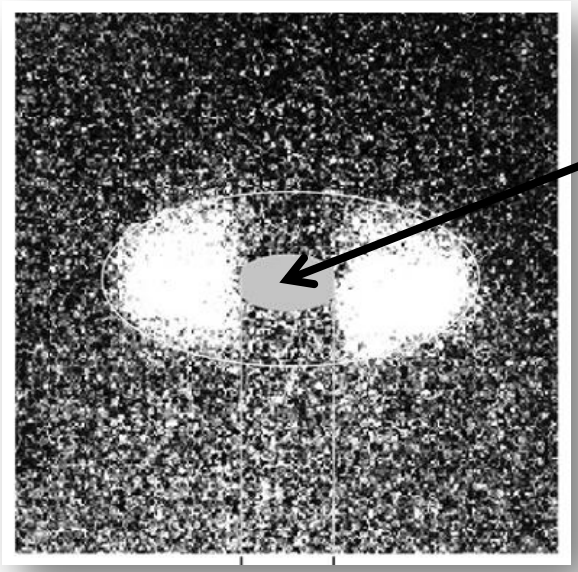
  cryogenic Penning trap

  Be^{+} cools Xe^{34+}

  L. Gruber et al., PRL **86**, 636 (2001)

  P L. Gruber et al., Physica Scripta. 71, (2005)

High resolution CCD images of Be^{+} and Xe^{34+} clouds.



- Proposals:

  M. Bussmann et al., Int. J. Mass Spectr. **251**, 179

  M. Bussmann et al., Hyperfine Interact. **173**, 27–34 (2007)

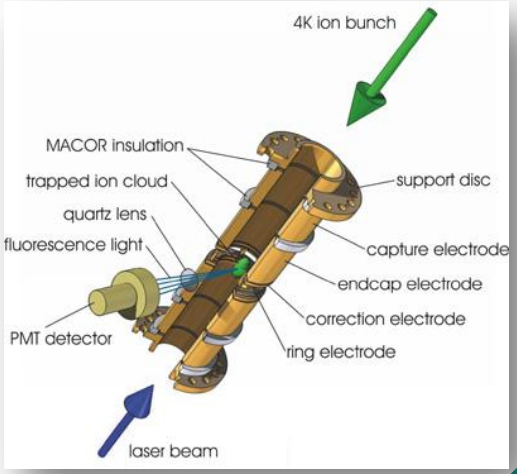
- SPECTRAP @ GSI

Resistive cooling &

$^{24}Mg^{+}$ ion cloud laser cooled in Penning trap

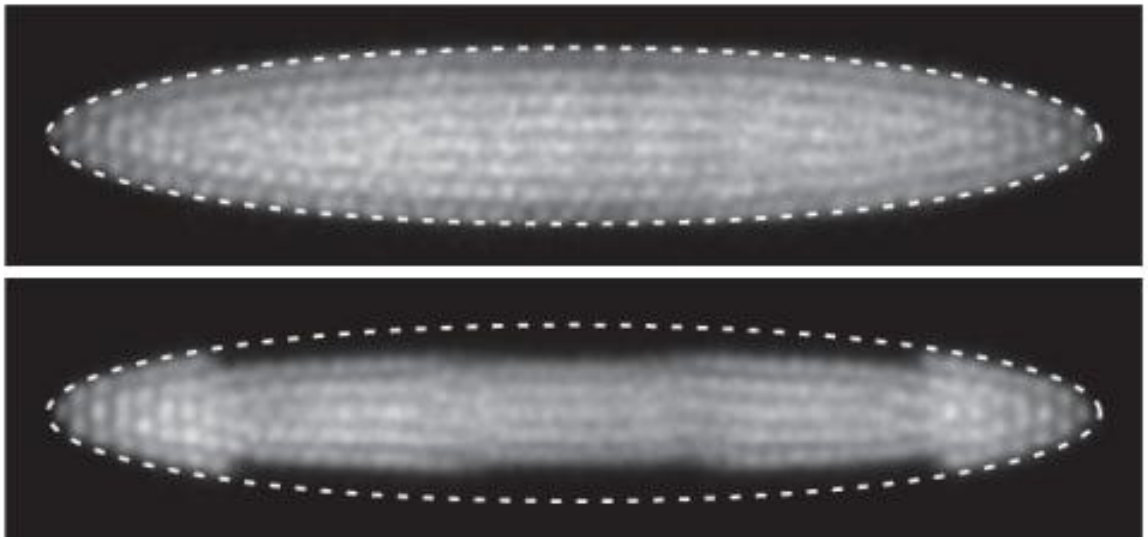
R. Cazan et al., Hyperfine Interact. **196**, 177–189 (2010)

Z. Andelkovic, arXiv:1211.2106 (2012)



Sympathetic Cooling of HCIs
in a Paul trap

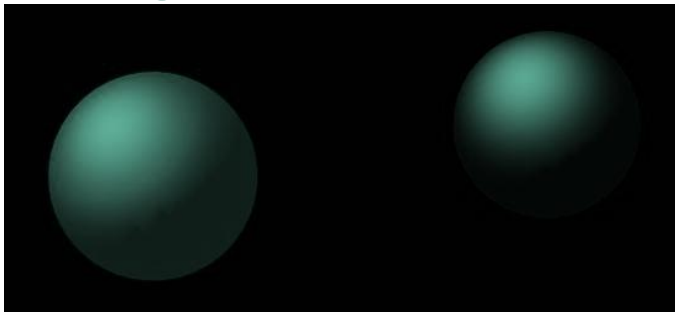
Coulomb crystal



- Can store many ions
- Temp. < 100mK (compare: 10^5K!) …micromotion
- Be^+ as sympathetic coolant; optimal q/m

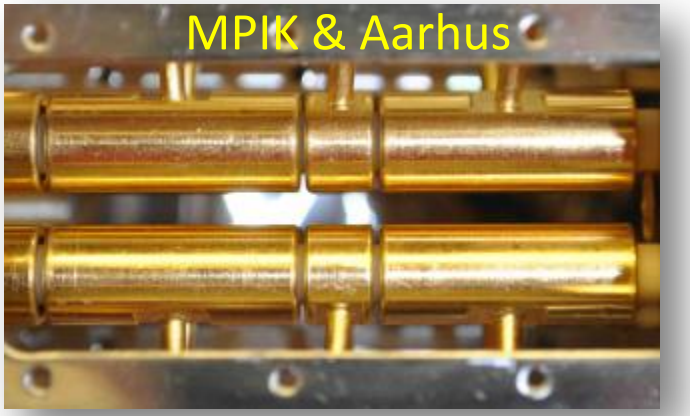
P. F. Staanum, (Michael Drewsen) *et al.* , Nature Physics **6** (2010)

2 single-ion Coulomb crystal



- Only 1 HCI for highest accuracy
- Need quantum logic readout

Sympathetic Cooling of HCIs in a cryogenic Paul trap



- Cryogenic linear Paul trap at T=4K
- Injection of HCIs from EBIT at MPIK
- Sympathetic cooling of HCIs with Be+
- Quantum logic readout with PTB for highest accuracy

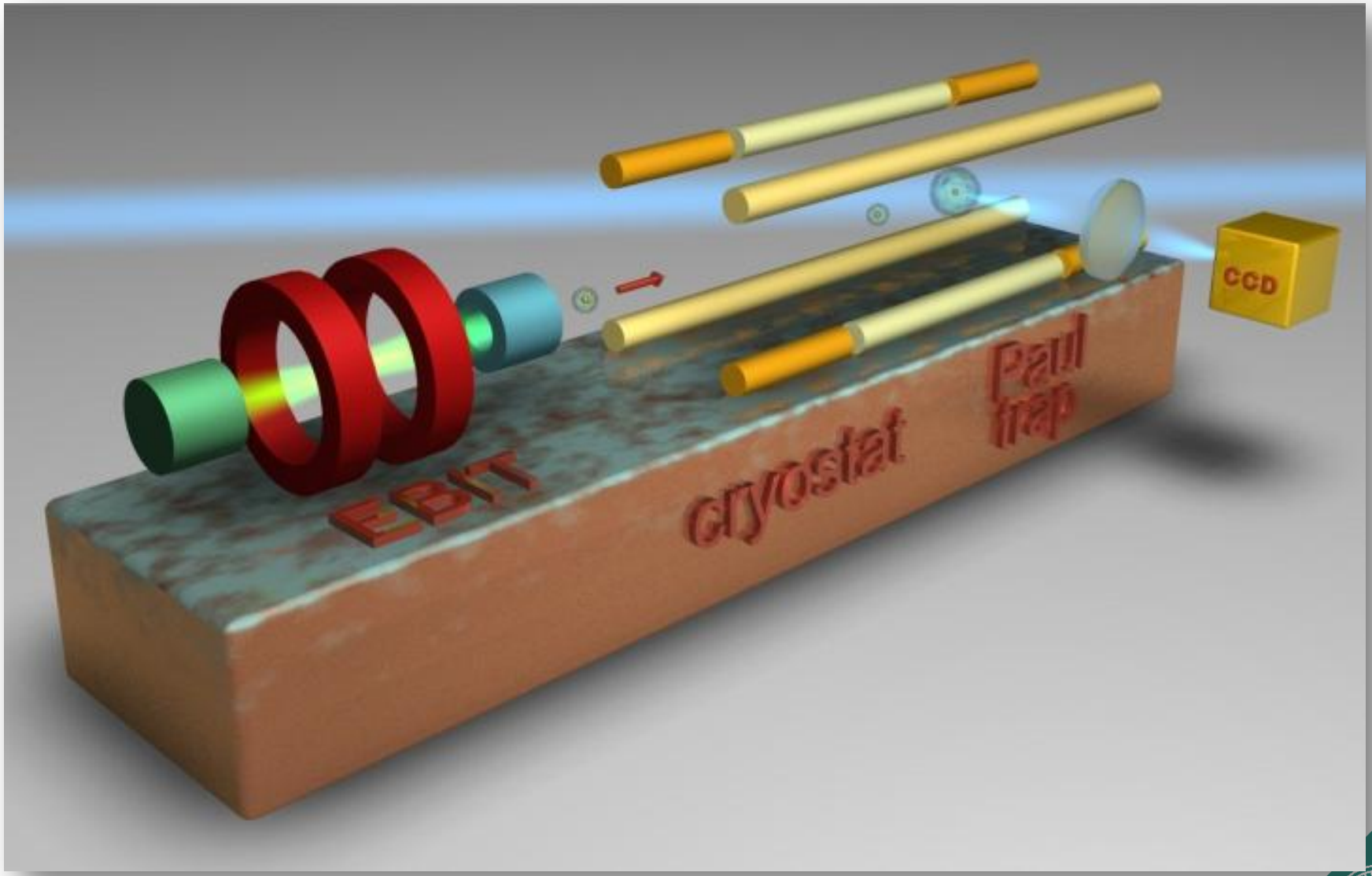
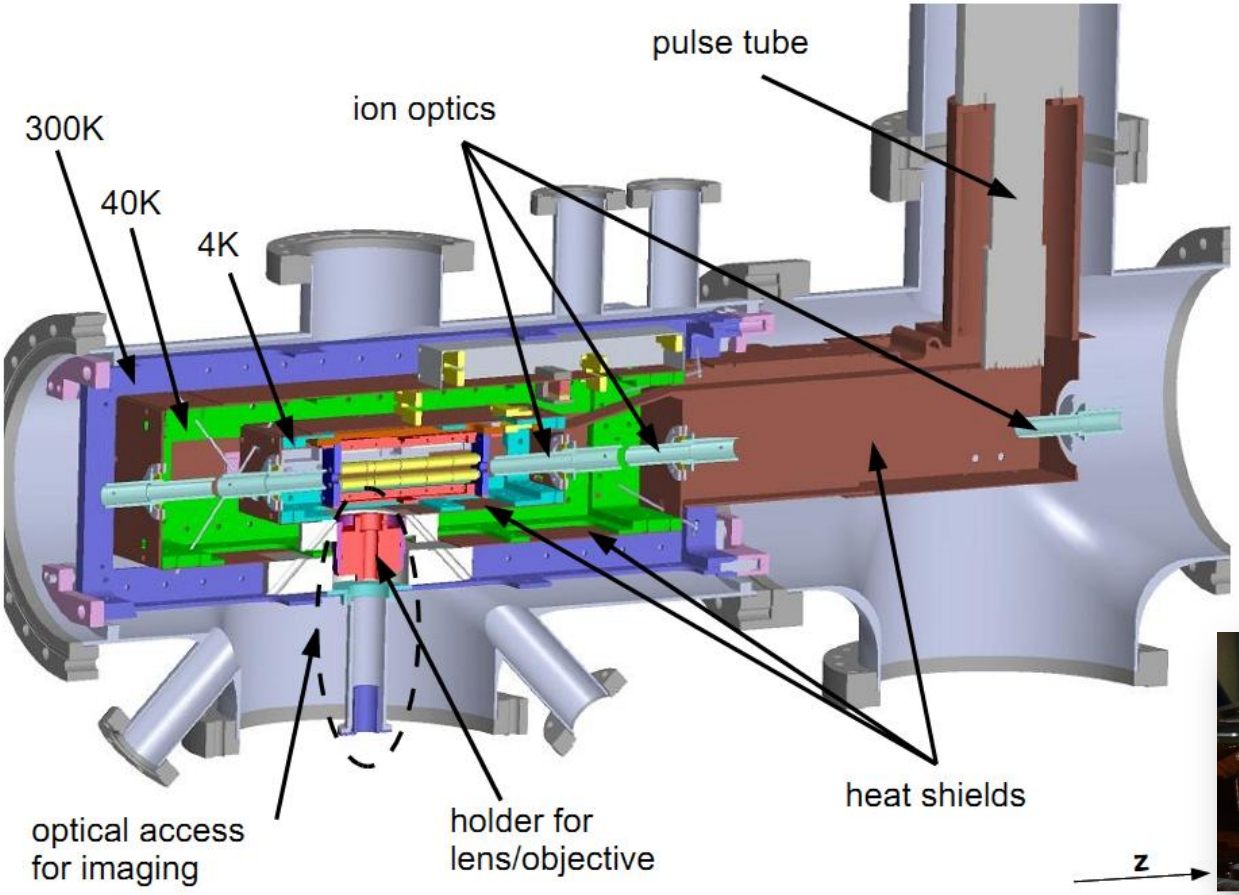


Image by P.O. Schmidt

Cryogenic Paul Trap Experiments

A cryogenic linear RF ion trap for sympathetic laser cooling of HCIs and molecular ions

M. Schwarz, *et al.,* Rev. Sci. Instr. **83** (2012)



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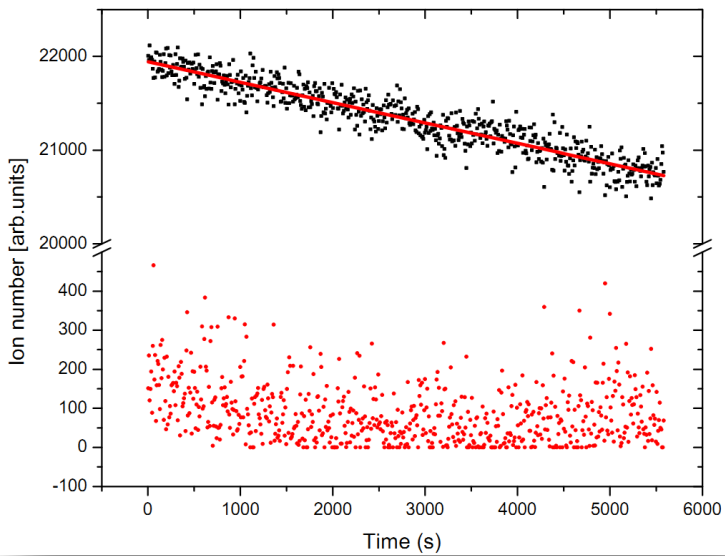
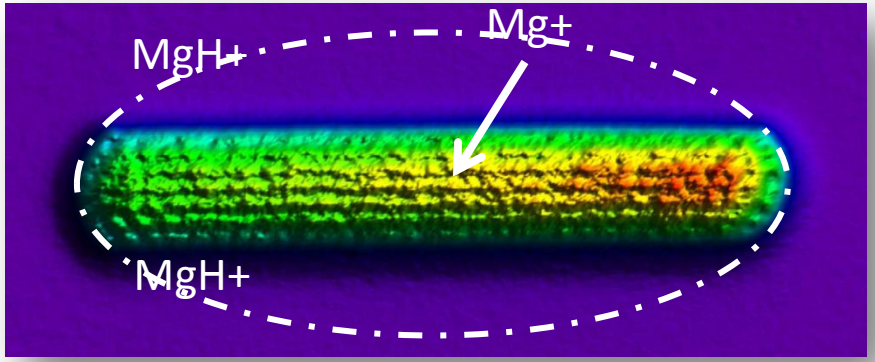


- UHV vacuum < 10^{-14} mbar (H_2@ 4K)
- Low exposure to 300K blackbody fields
- Plentiful optical access ports
- Commissioned with Mg^+ and MgH^+ in Aarhus (Michael Drewsen's Ion Trap group)



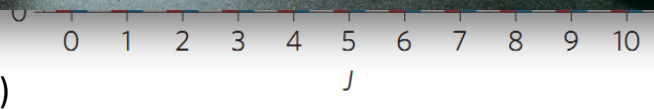
Experiments with cooled MgH+

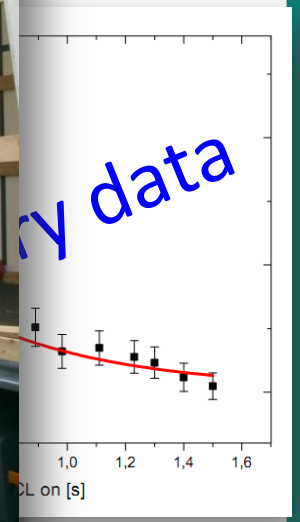
intermezzo

Preparing externally and internally ultra-cold molecular ions

with the lo

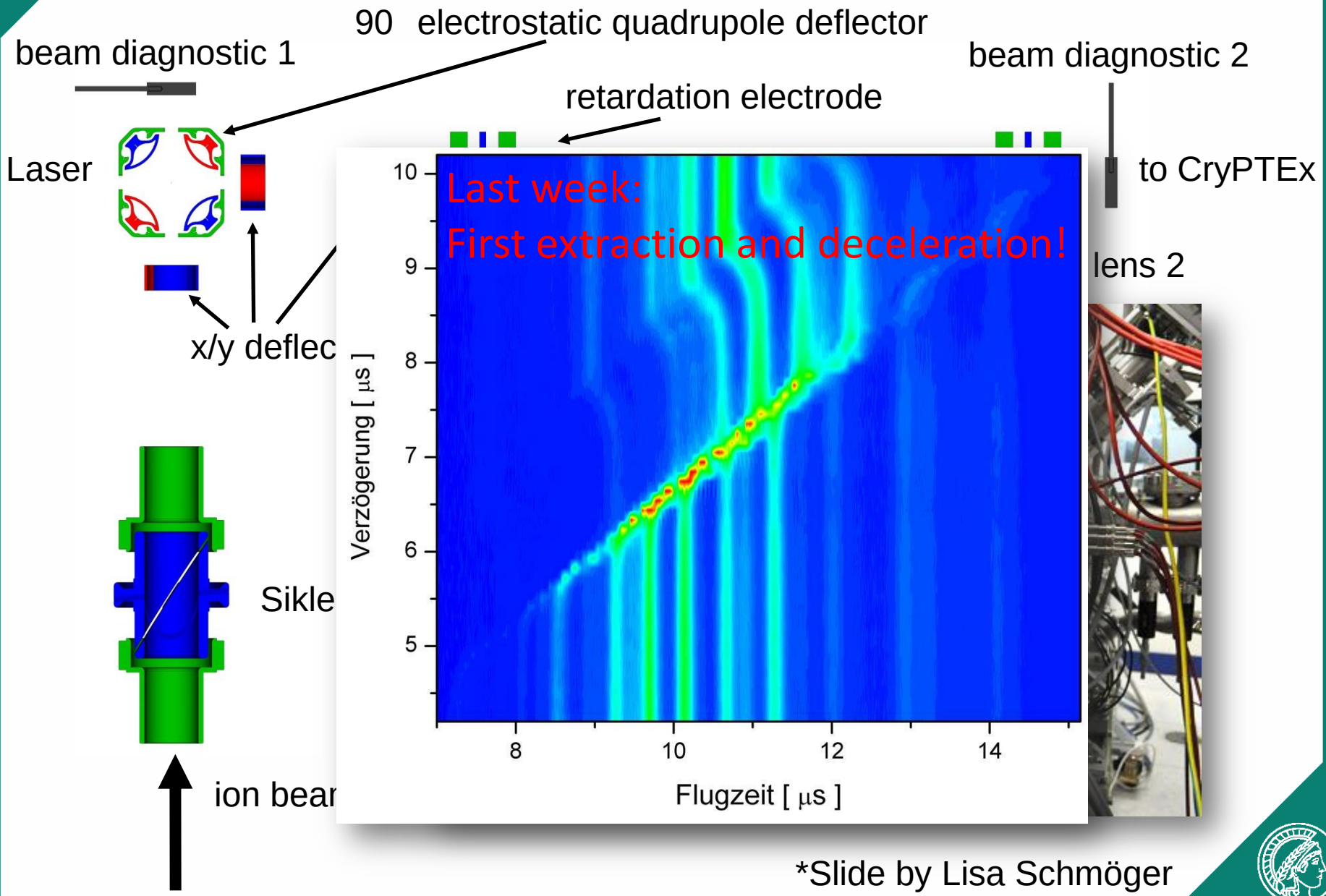
Experiment wit





P. F. Staanum *et al.,* Nature Physics **6** (2010)

Extr. and injection beamline*

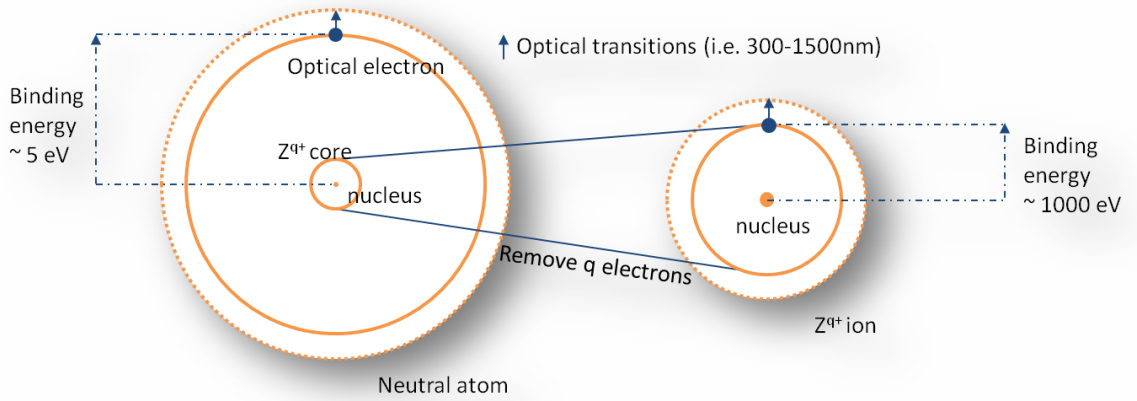


*Slide by Lisa Schmöger

Be^+ laser systems

Similar to: A. C. Wilson et al., Appl. Phys. B **105**, 741 (2011)

Highly charged ions for metrology



- Strongly bound electrons
- Low susceptibility to certain external field shifts:
  - Second order Zeeman shift

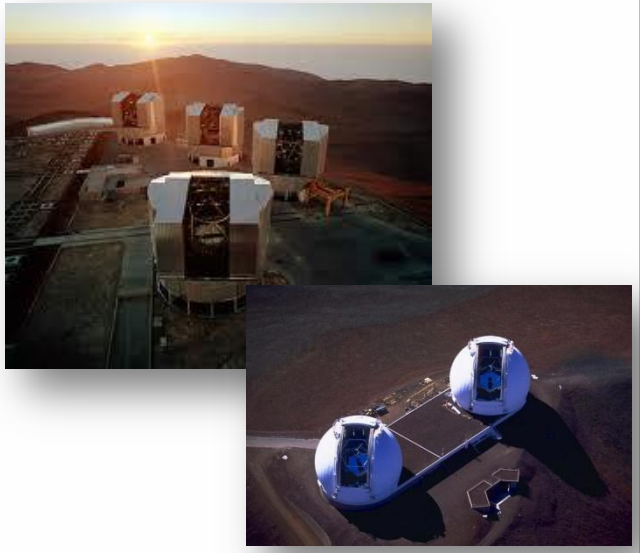
    $\sim 1/Z_h^2$ (BUT: linear shift ~MHz/G)
  - Stark shifts (BBR, light shift, trap induced, quadrupole)

    BBR $\sim 1/Z_a^4$

Variation of alpha

- Quasar absorption spectra
  - *"Australian dipole" at 4σ*
  - *$\alpha/\alpha \sim 10^{-19}$/year*

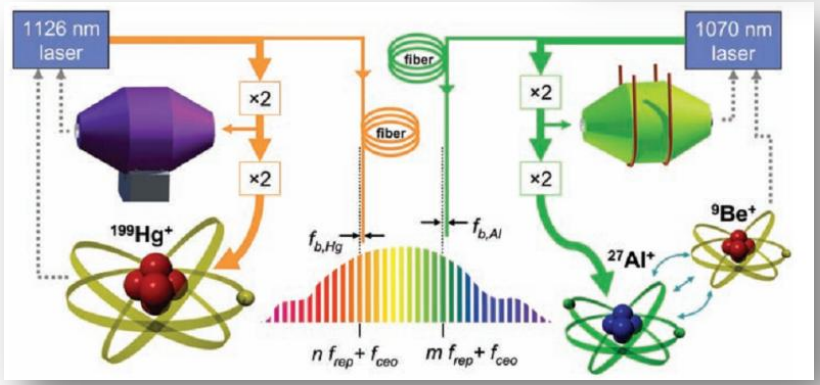
Berengut et al, Europhys. Lett. 97, 20006 (2012)
Webb et al., PRL 107, 191101 (2011)



- *Hg+/Al+ Atomic clocks*
  - *$-1.6(2.3) \times 10^{-17}$/year*

Rosenband et al., Science 319 (2008)

  - *Need 100x improvement!*



Highly charged ions for α-dot

$$\omega \approx \omega_0 + 2q\Delta\alpha/\alpha$$

Strong relativistic effects, enhanced sensitivity:

- High nuclear charge *Z*
- High ionization potential I_n

$$q \approx -I_n \frac{(Z\alpha)^2}{\nu(j+1/2)}$$

Berengut et al., PRL 105, 120801 (2010)

- Differences in the configuration composition (i.e. ν, *j*)
- Scaling even faster with *hole transitions*

$$q \sim I_n^{3/2}$$

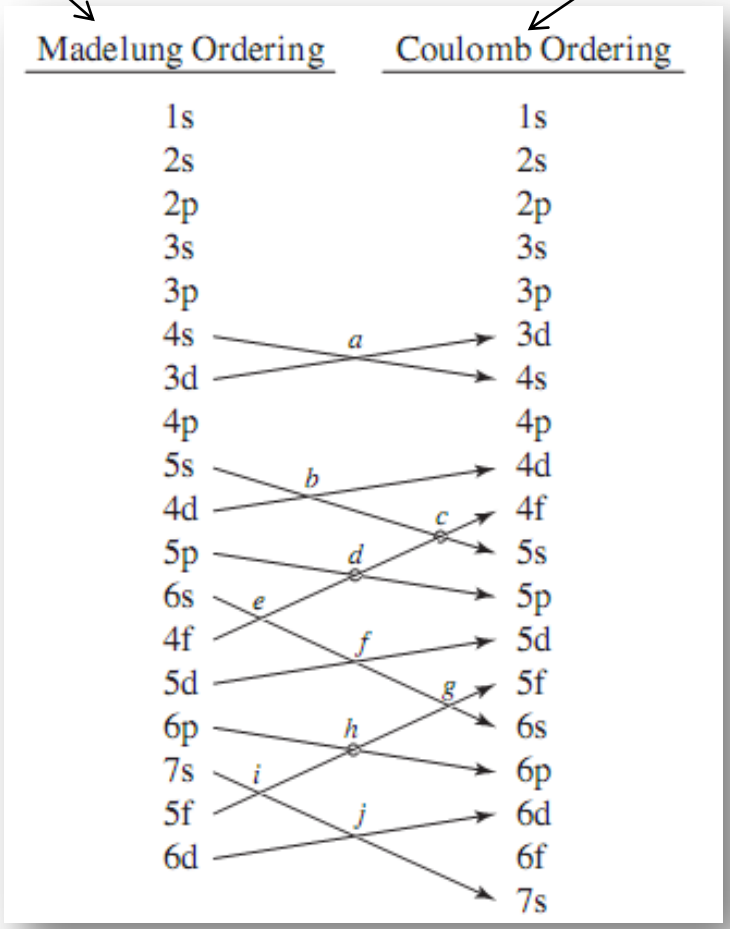
Berengut et al., PRL 106, 210802 (2011)

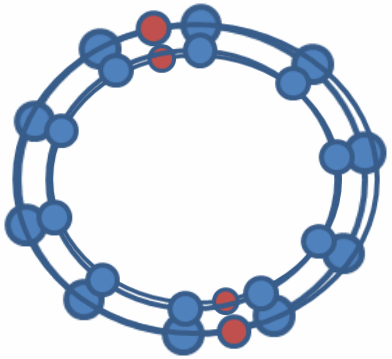
BUT: need to keep transitions in optical regime…

Level crossings: optical transitions

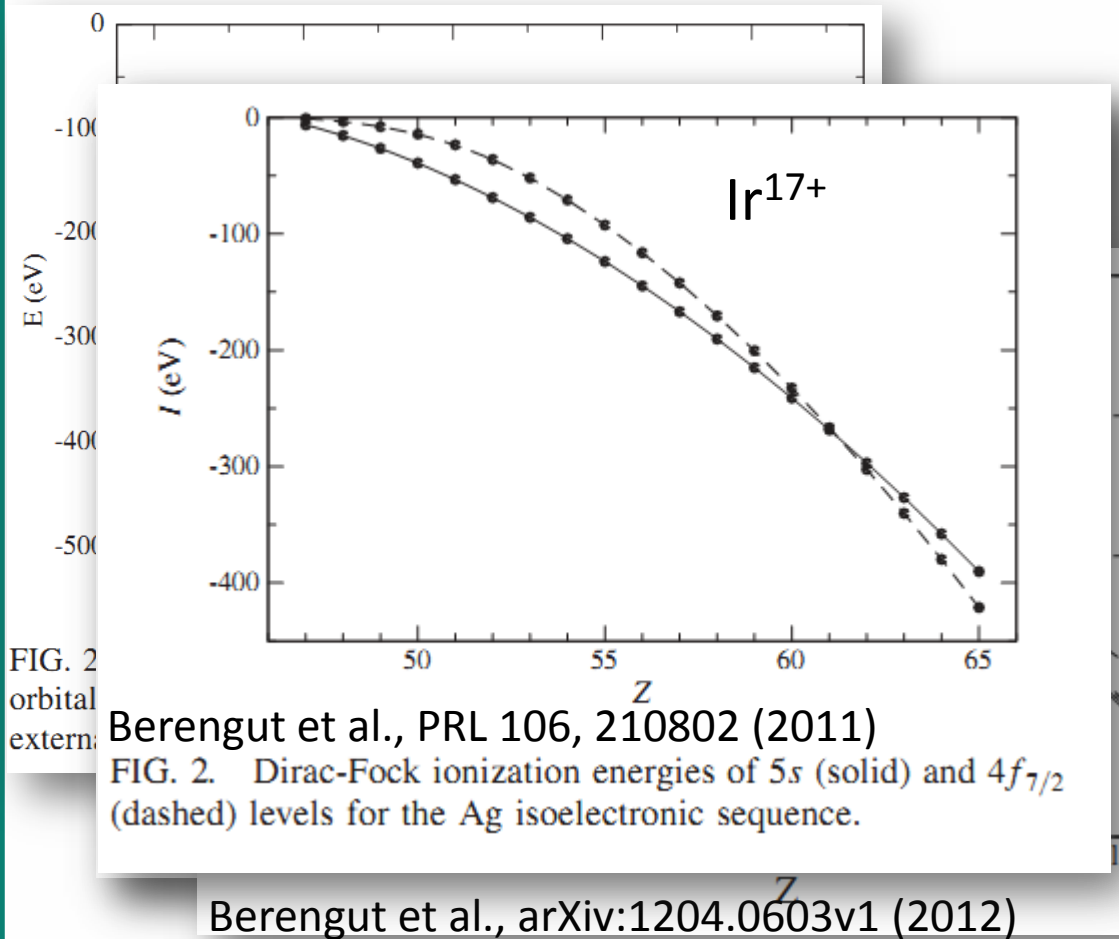
neutral

hydrogen-like





Level crossings: optical transitions



Berengut et al., PRL 106, 210802 (2011)

FIG. 2. Dirac-Fock ionization energies of $5s$ (solid) and $4f_{7/2}$ (dashed) levels for the Ag isoelectronic sequence.

Berengut et al., arXiv:1204.0603v1 (2012)

q ~ 140,000 cm^{-1}

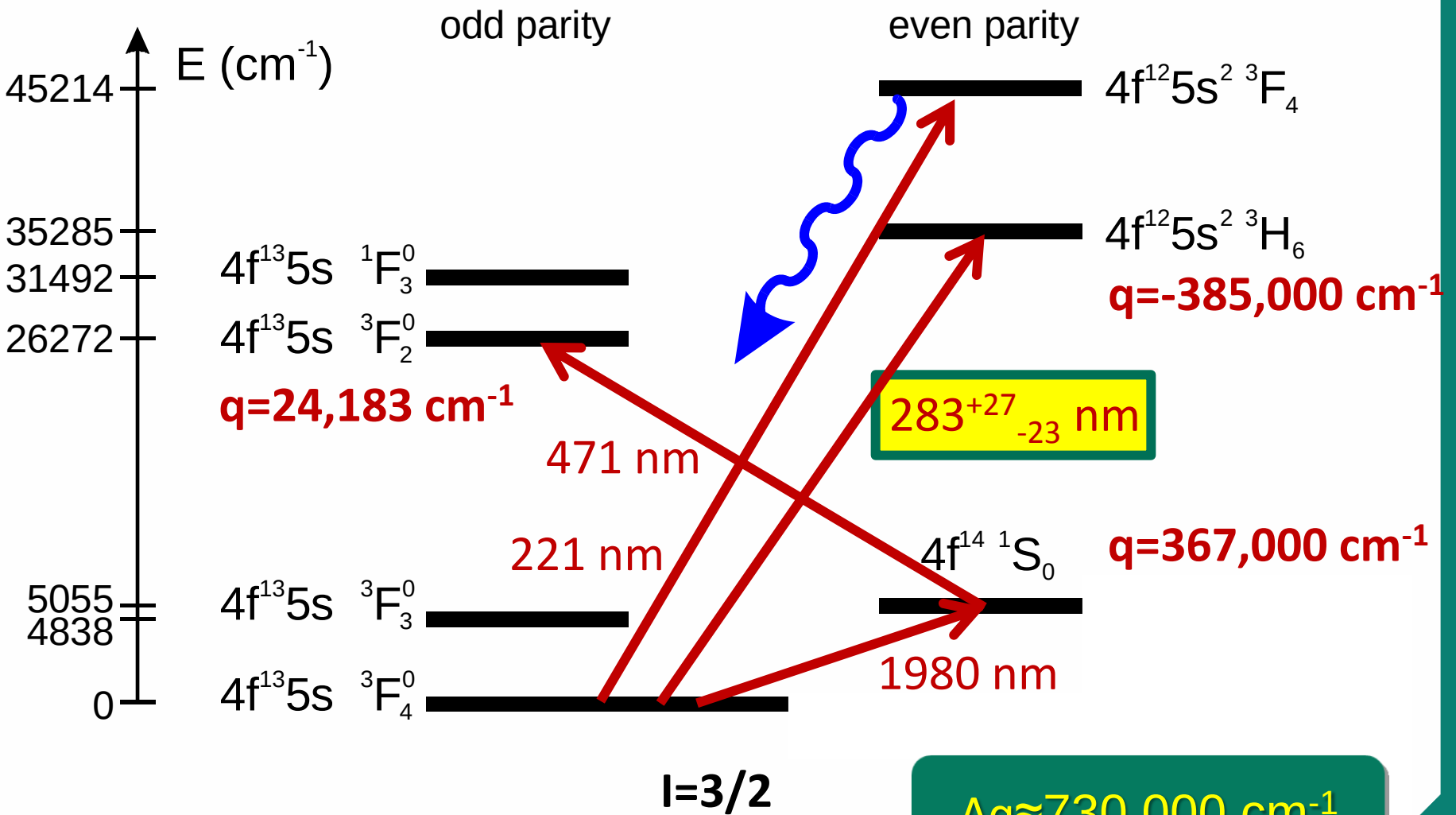
q ~ 370,000 cm^{-1}

q ~ 450,000 cm^{-1}

Compare: Hg+ at

q ~ 52,200 cm^{-1}

$^{193}Ir^{17+}$ partial level structure*



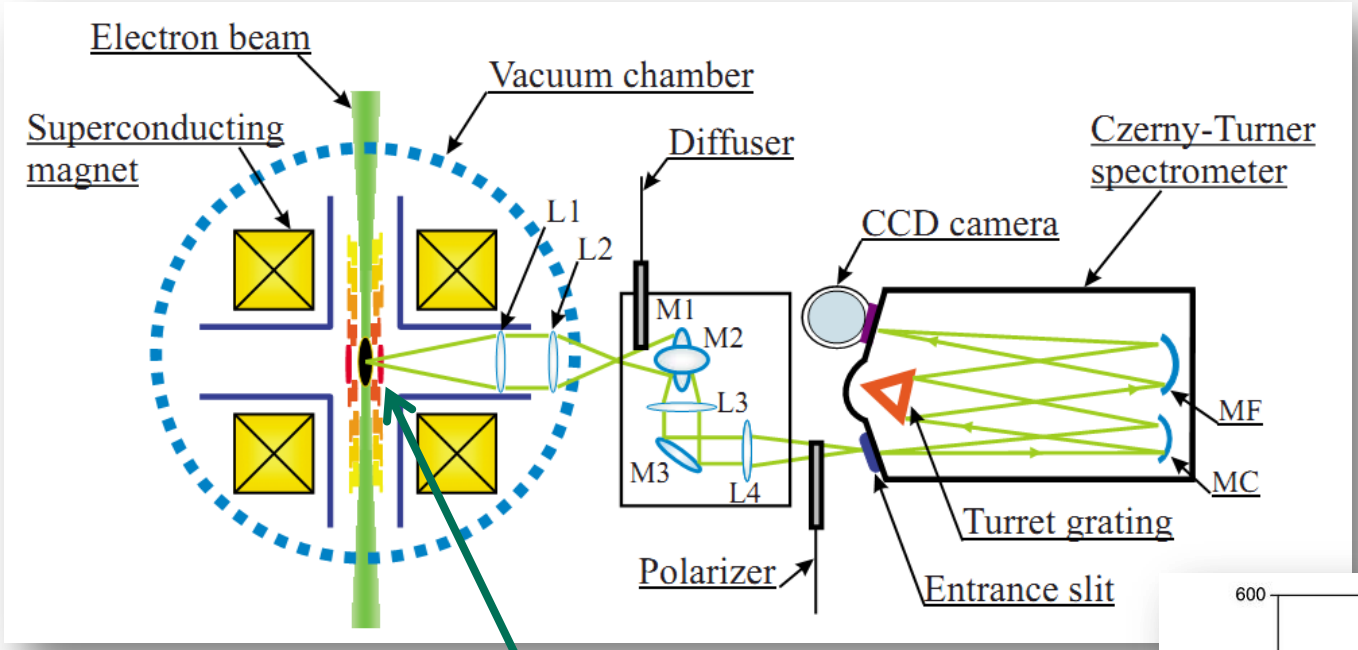
Δq≈730,000 cm^{-1}

Accuracy of calculation: 6000 cm^{-1}

Berengut *et al.*, PRL **106**, 210802 (2011)

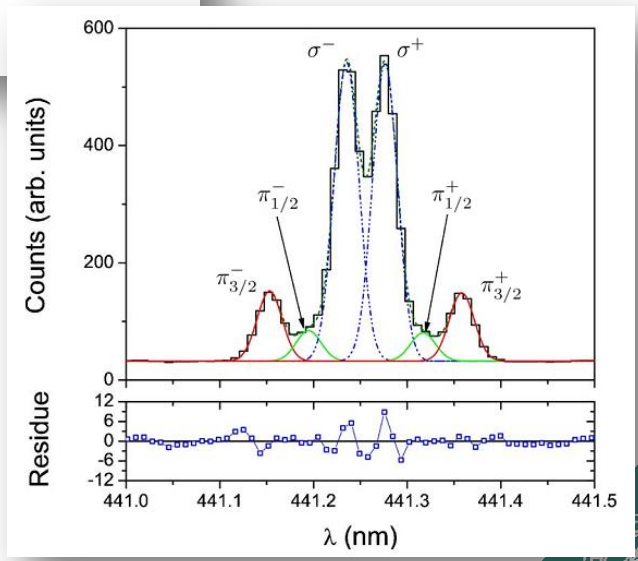
*Slide courtesy of P.O. Schmidt

EBIT fluorescence spectroscopy



Orts et al., PRA 76, 052501 (2007)
Orts et al., PRL 97, 103002 (2006)

$^{193}Ir^{17+}$



EBIT fluorescence spectroscopy

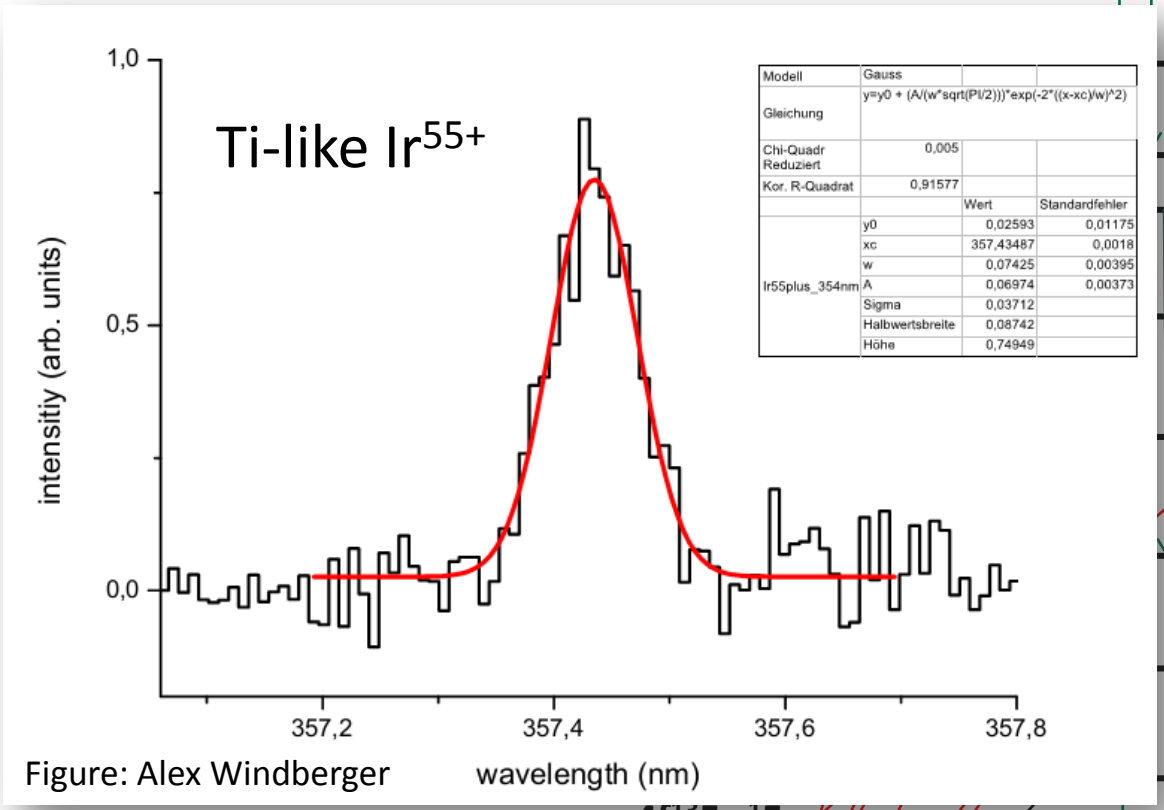
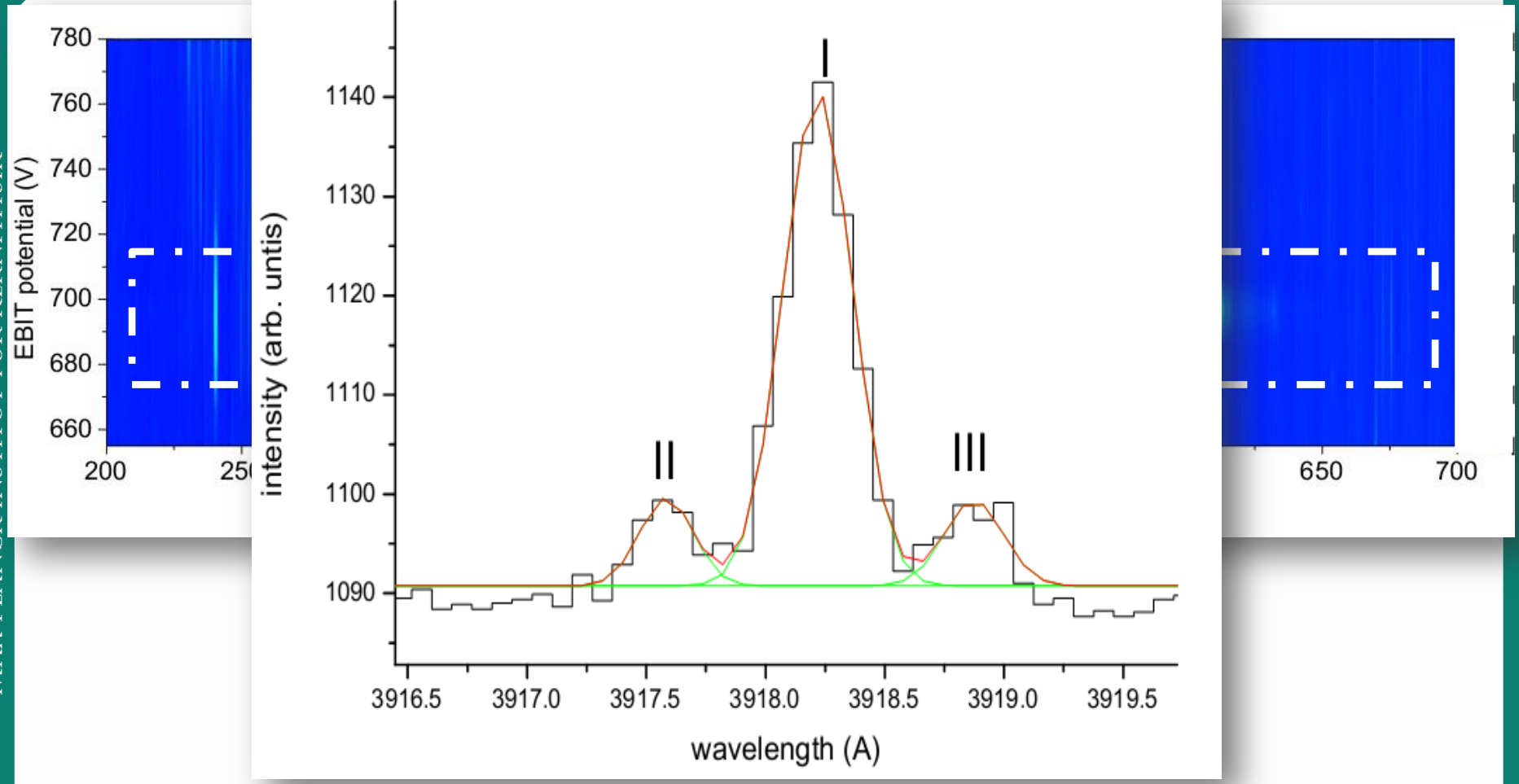


Figure: Alex Windberger

EBIT fluorescence spectroscopy

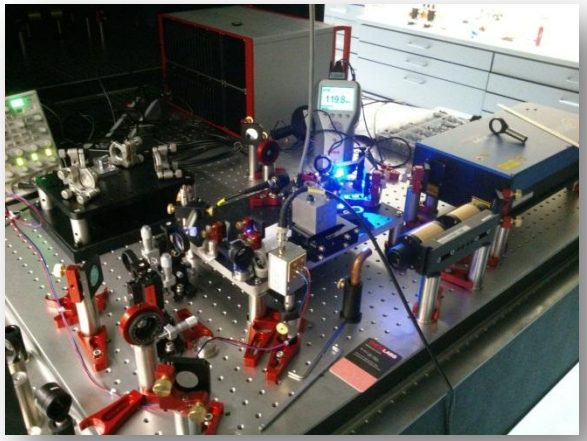


- Line identification by scanning electron beam energy

Figures: Alex Windberger, Hendrik Bekker

Summary & Outlook

- Highly charged ions for metrology and fundamental physics.
- Cryogenic Paul commissioned with MgH^+ at Aarhus University
- Ir^{17+} excellent candidate. EBIT spectroscopy underway.
- Be^+ cooling laser system operational. Construction of PI and spectroscopy lasers underway at PTB.



The crew & acknowledgements

Experiment\MPIK

- M. Schwarz
- A. Windberger
- L. Schmöger
- S. Bieling
- O. O. Versolato
- *J. Ullrich*
- J. Crespo López-Urrutia







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- S. B. Kristensen
- A. Hansen
- A. D. Gingell
- L. Klosowski
- M. Drewsen




Experiment\PTB

- P. O. Schmidt (PTB)
- J. Ullrich

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