MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

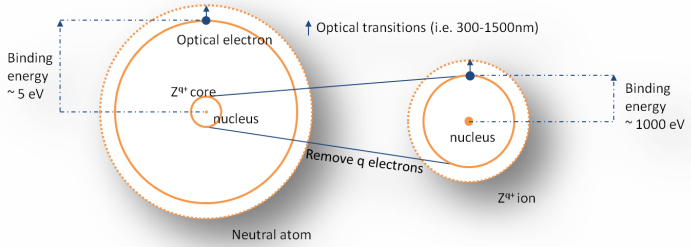
Cold Highly Charged Ions in a Cryogenic Paul Trap

Oscar O. Versolato

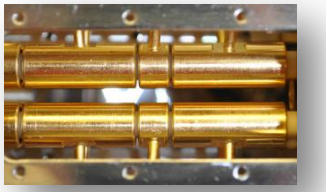
Max-Planck-Institut für Kernphysik, D-69117 Heidelberg

Experimental Few-Particle Quantum Dynamics

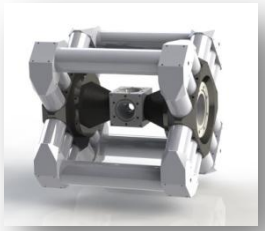
Overview

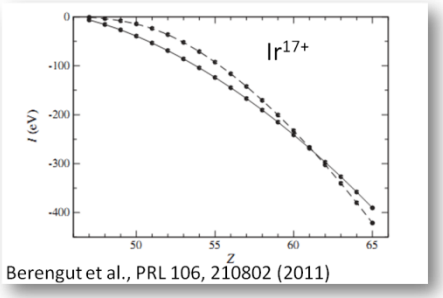


- Highly charged ions for metrology and fundamental physics
- Cryogenic Paul trap for sympathetic cooling of HCIs



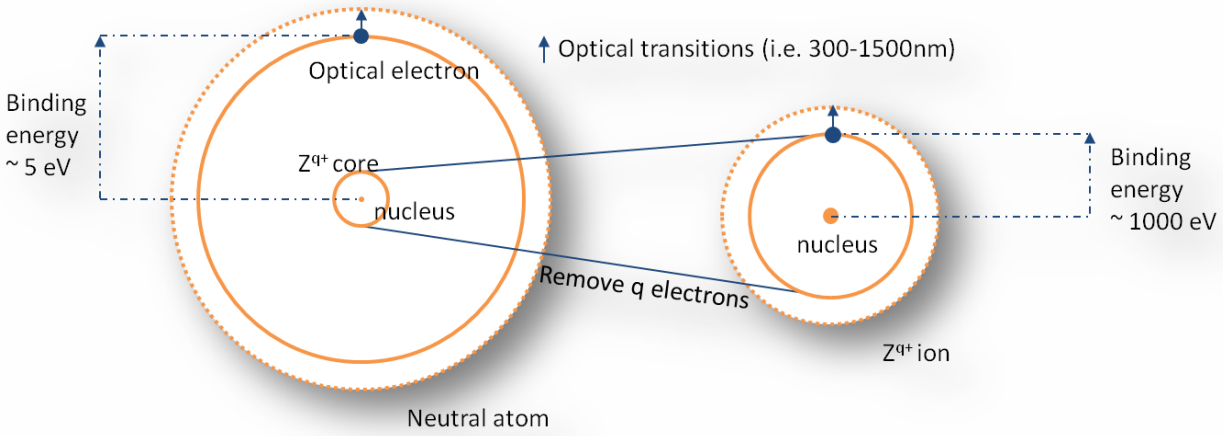
- Ir^{17+} and time variation of fine structure constant
- Outlook





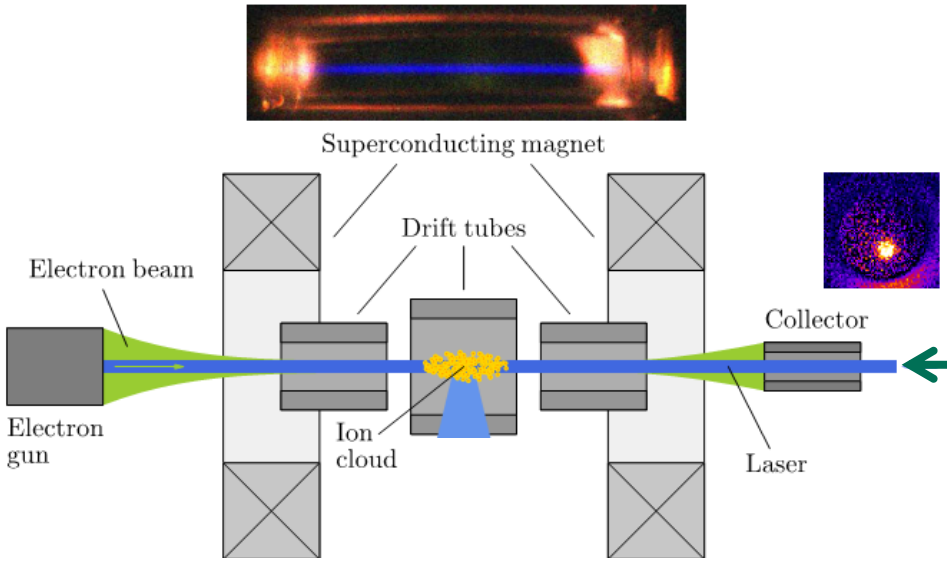
Berengut et al., PRL 106, 210802 (2011)

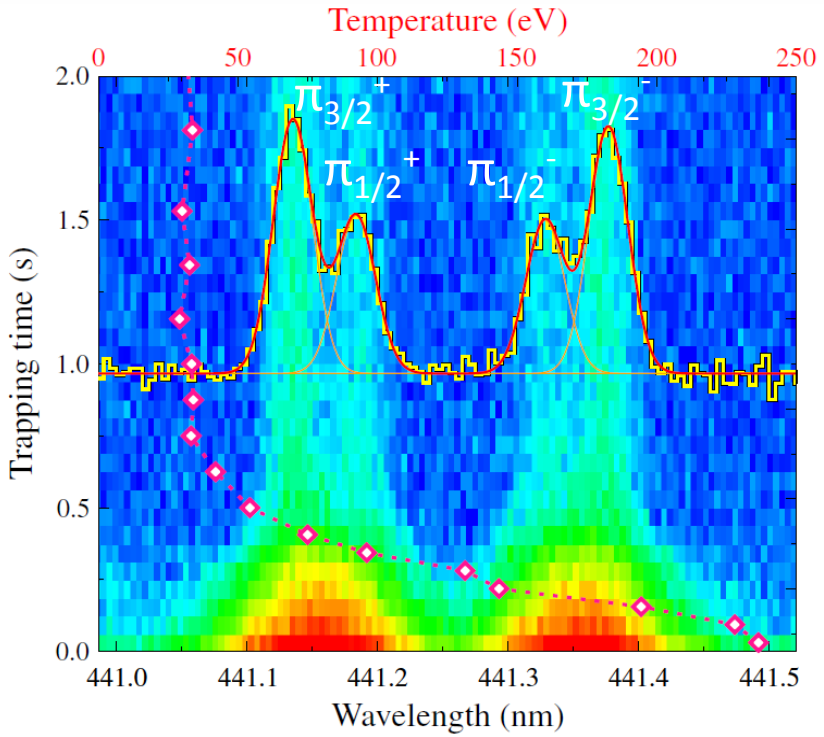
Highly charged ions, scaling laws



- 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





V. Mäckel, et al., PRL. **107**, 143002 (2011)

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

Evaporatively cooled from 240 to 28eV (10eV achieved)

Limited by Doppler line width! Need cooling…

Sympathetic Cooling of HCIs

- RETRAP (LLNL):

  cryogenic Penning trap

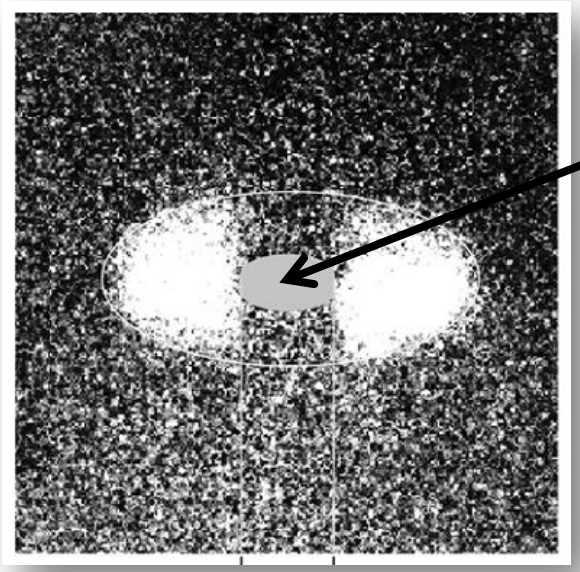
  Be^{+} cools Xe^{34+}

  Temperature: ~1 K

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

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

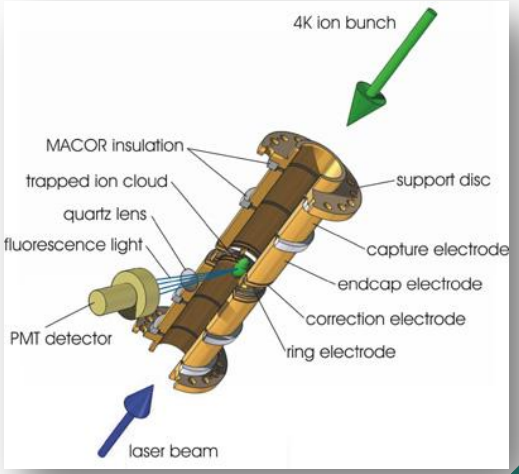
High resolution CCD images of Be^{+} and Xe^{34+} clouds.



- Proposals:

  M. Bussmann et al., Int. J. Mass Spectr. **251**, 179 (2006)

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



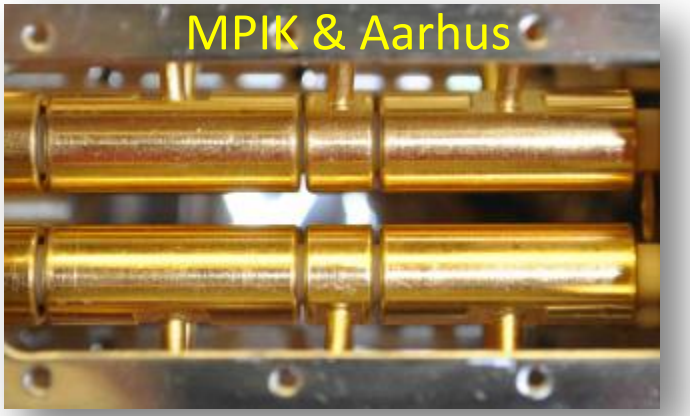
- SPECTRAP @ GSI

Resistive cooling &

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

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

Sympathetic Cooling of HCIs in a cryogenic Paul trap

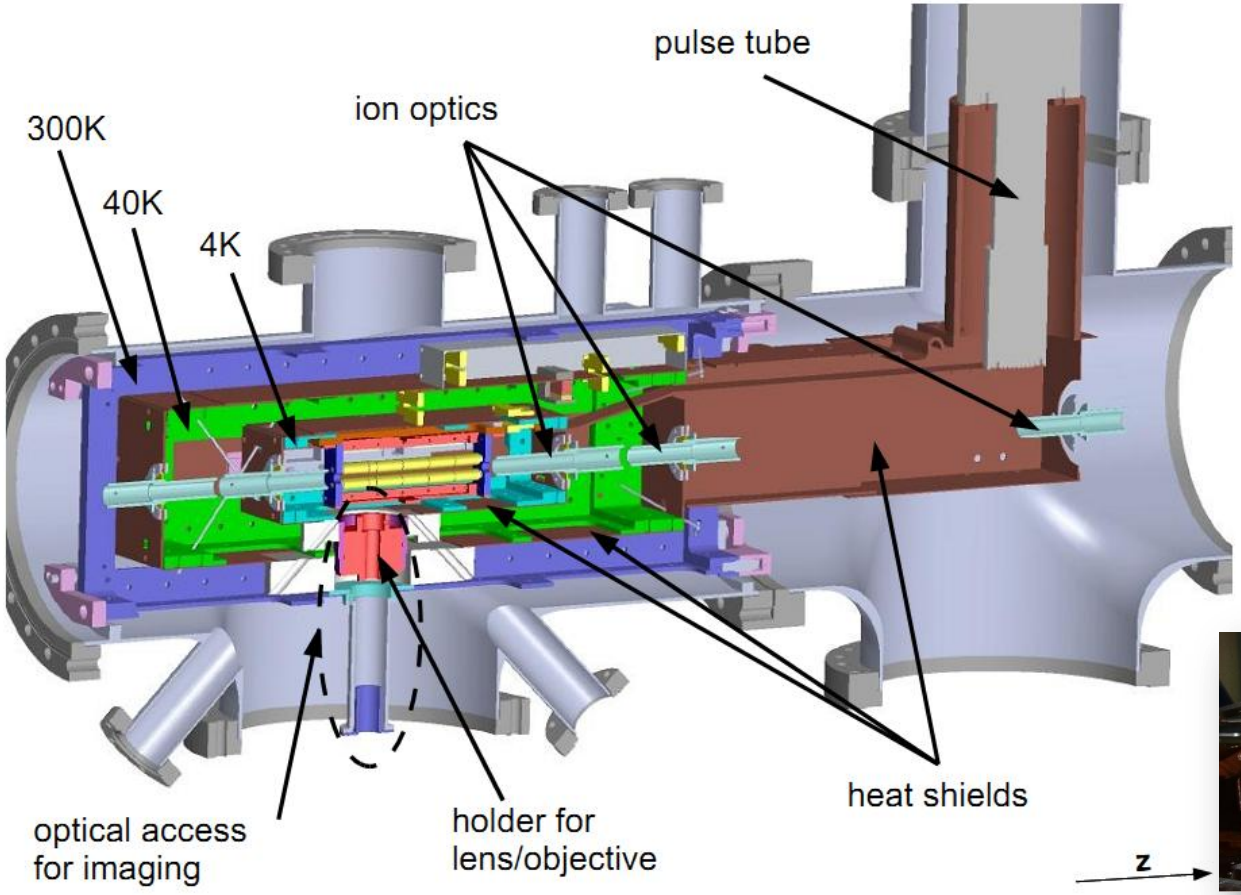


- Cryogenic linear Paul trap at T=4K
- Injection of HCIs from EBIT at MPIK
- Sympathetic cooling of HCIs with laser-cooled Be+ created thru PI
- Quantum logic readout with PTB for highest accuracy

Cryogenic Paul Trap Experiments

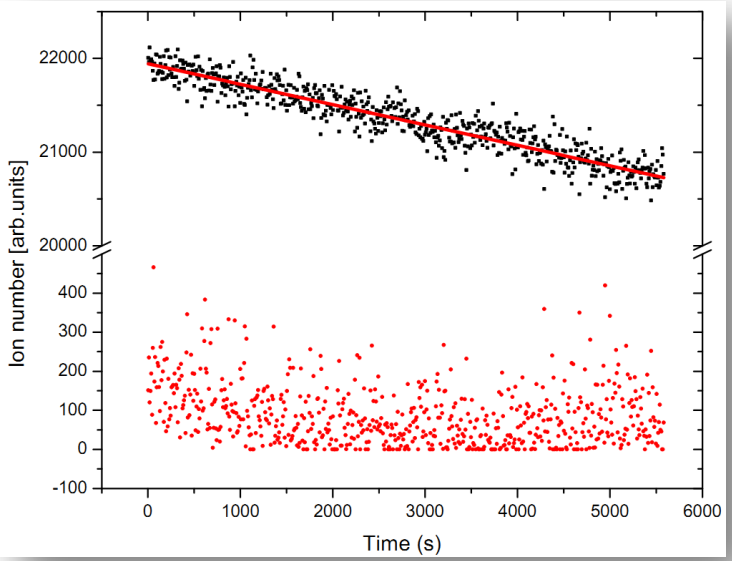
A cryogenic linear RF ion trap for sympathetic laser cooling of HCIs and molecular ions

M. Schwarz, *et al.,* Rev. Sci. Instr. *submitted*

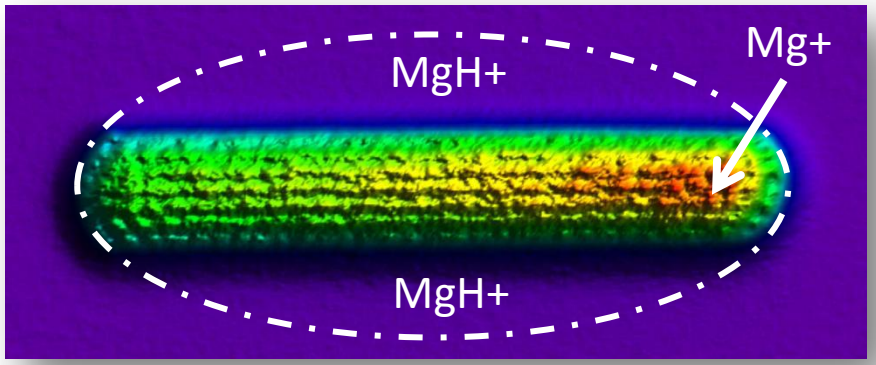


Cryogenic Paul Trap Experiments

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



- 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 (Drewsen group)

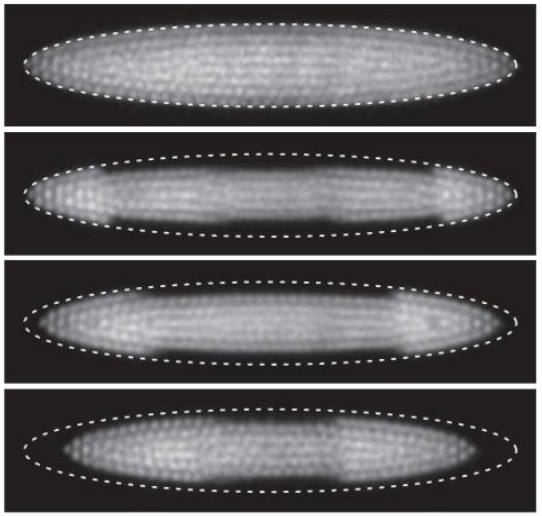


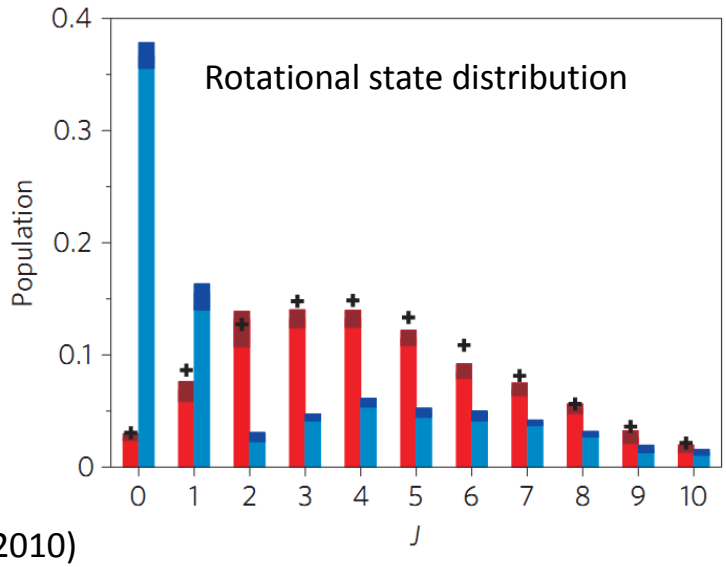
Experiments with cooled MgH+ *intermezzo*

Preparing externally and internally ultra-cold molecular ions

with the Ion Trap Group at Aarhus University

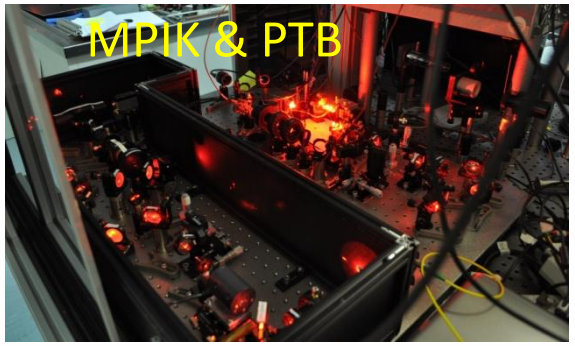
Ongoing experiment with exciting results. *Stay tuned...*





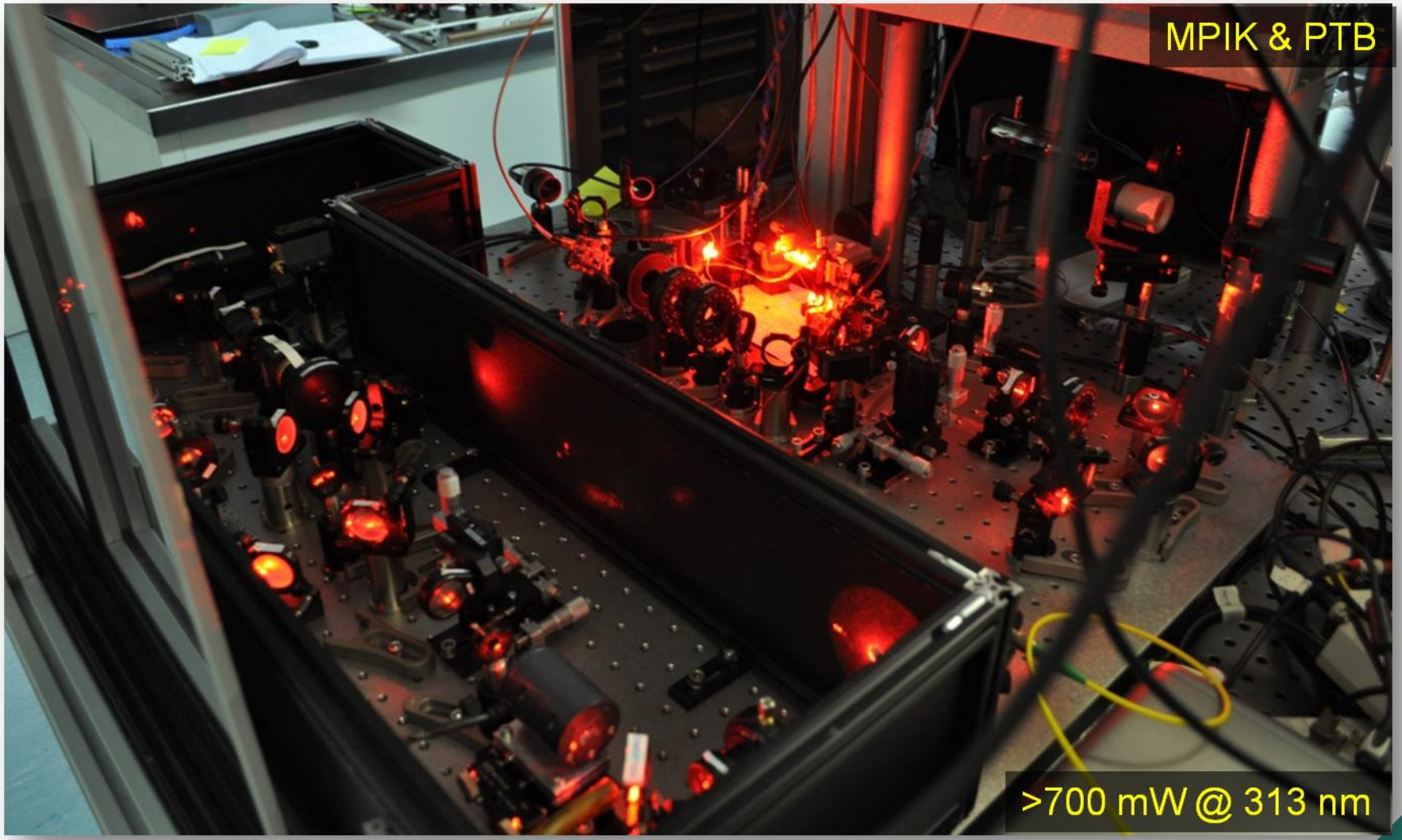
P. F. Staanum *et al.,* Nature Physics **6** (2010)

Sympathetic Cooling of HCIs in a cryogenic Paul trap



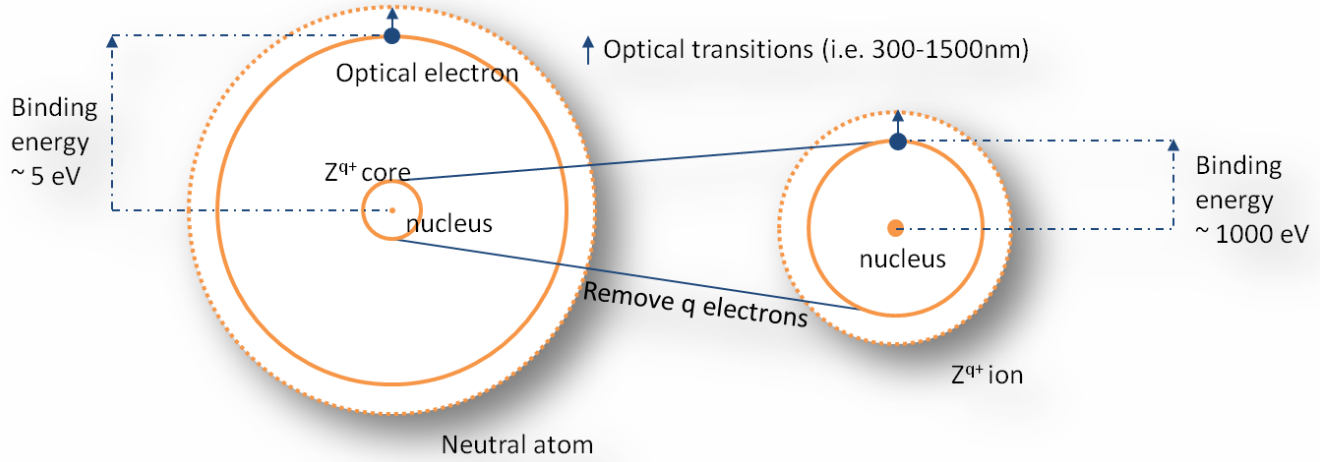
- *Cryogenic linear Paul trap at T=4K*
- *Injection of HCIs from EBIT at MPIK*
- Sympathetic cooling of HCIs with laser-cooled Be+ created thru PI
- Quantum logic readout with PTB for highest accuracy

Be+ laser system at 313nm



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 $\sim 1/Z_a^4$

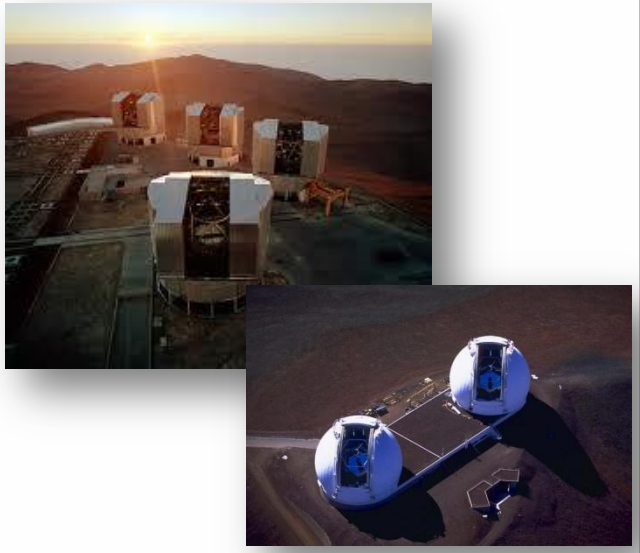
Makes for high-accuracy atomic clock

Variation of alpha

Webb et al., PRL 107, 191101 (2011)

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

Berengut et al, Europhys. Lett. 97, 20006 (2012)



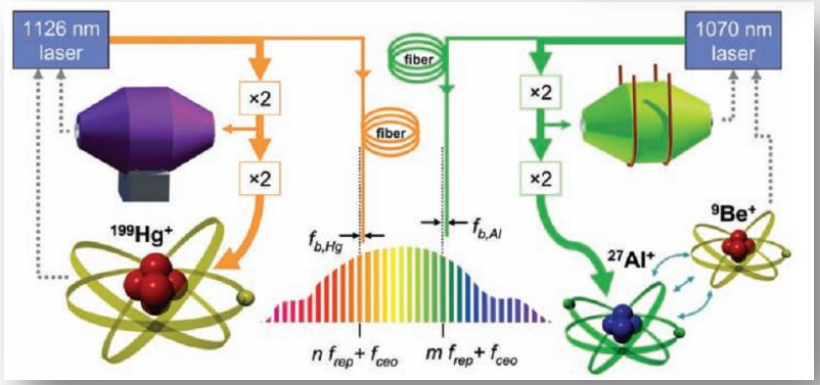
- Oklo natural reactor
  - *< 3 x 10^{-17}/year (however…)*

e.g., Dent et al., PRD 79, 083533 (2009)

- *Hg+/Al+ Atomic clocks*
  - *-1.6(2.3) x 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*

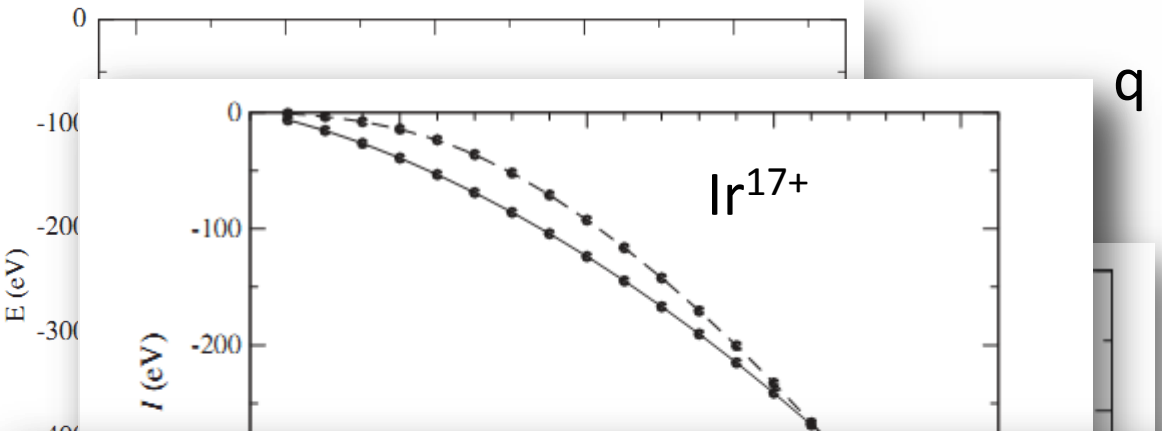
$$q \sim I_n^{3/2}$$

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

BUT: need to keep transitions in optical regime…

Level crossings: optical transitions

For high Z, $E_{5f}=E_{5p}$ but in neutral (thallium) $E_{5f}>E_{6p}$ so a level crossing is expected along isoelectronic sequences



q ~ 140,000 cm^{-1}

q ~ 370,000 cm^{-1}

q ~ 450,000 cm^{-1}

Highly charged ions with E1, M1, and E2 transitions within laser range

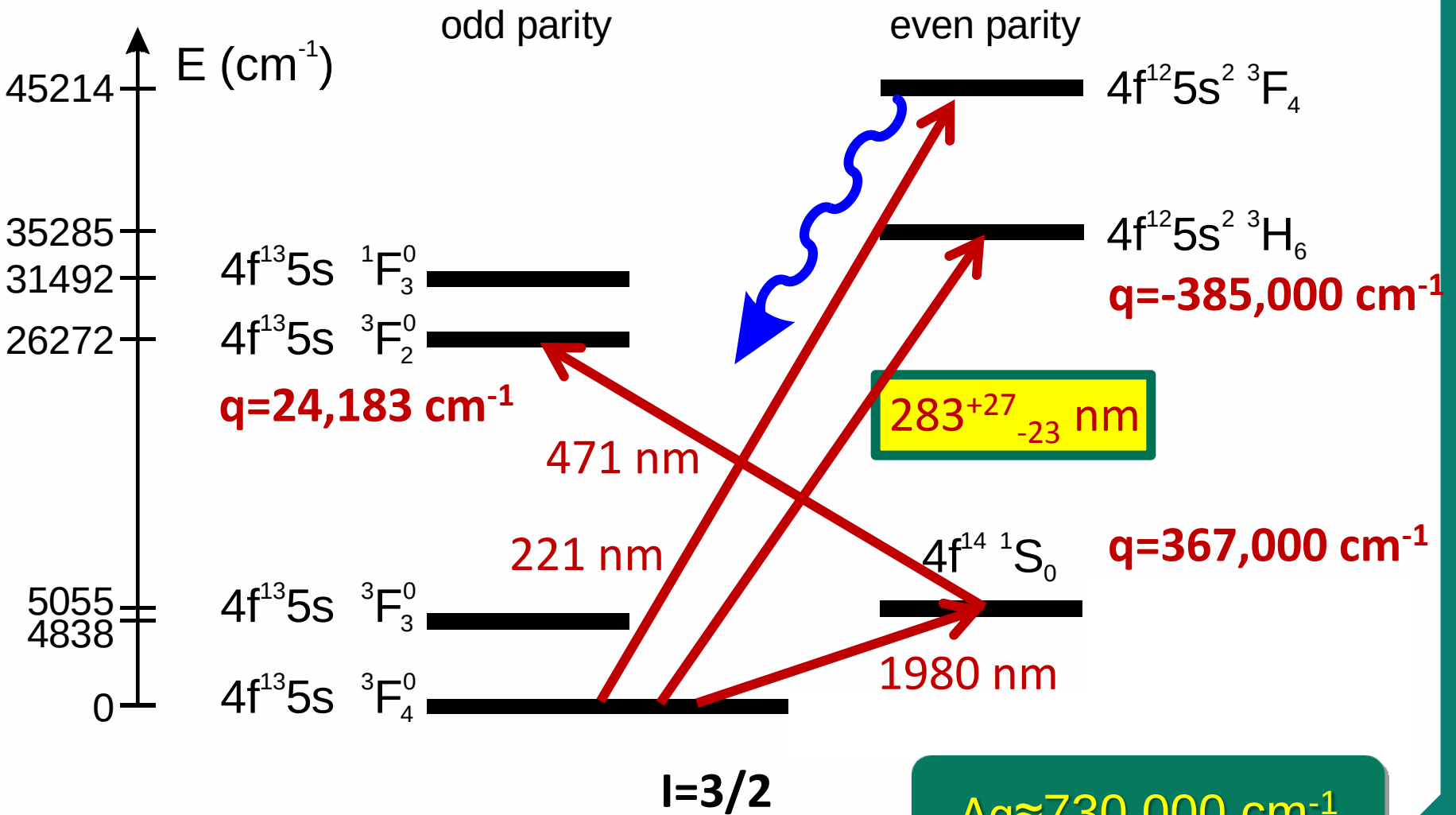
J. C. Berengut, V. A. Dzuba, V. V. Flambaum, and A. Ong
School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
(Dated: 4 June 2012)

Level crossings in the ground state of ions occur when the nuclear charge Z and ion charge $Z_{\rm ion}$ are varied along an isoelectronic sequence until the two outermost shells are nearly degenerate. We examine all available level crossings in the periodic table for both near neutral ions and highly charged ions (HCIs). Normal E1 transitions in HCIs are in X-ray range, however level crossings allow for optical electromagnetic transitions that could form the reference transition for high accuracy atomic clocks. Optical E1 (due to configuration mixing), M1 and E2 transitions are available in HCIs near level crossings. We present scaling laws for energies and amplitudes that allow us to make simple estimates of systematic effects of relevance to atomic clocks. HCI clocks could have some advantages over existing optical clocks because certain systematic effects are reduced, for example they can have much smaller thermal shifts. Other effects such as fine-structure and hyperfine splitting are much larger in HCIs, which can allow for richer spectra. HCIs are excellent candidates for probing variations in the fine-structure constant, α, in atomic systems as there are transitions with the highest sensitivity to α-variation.

Compare: Hg+ at

q ~ 52,200 cm^{-1}

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



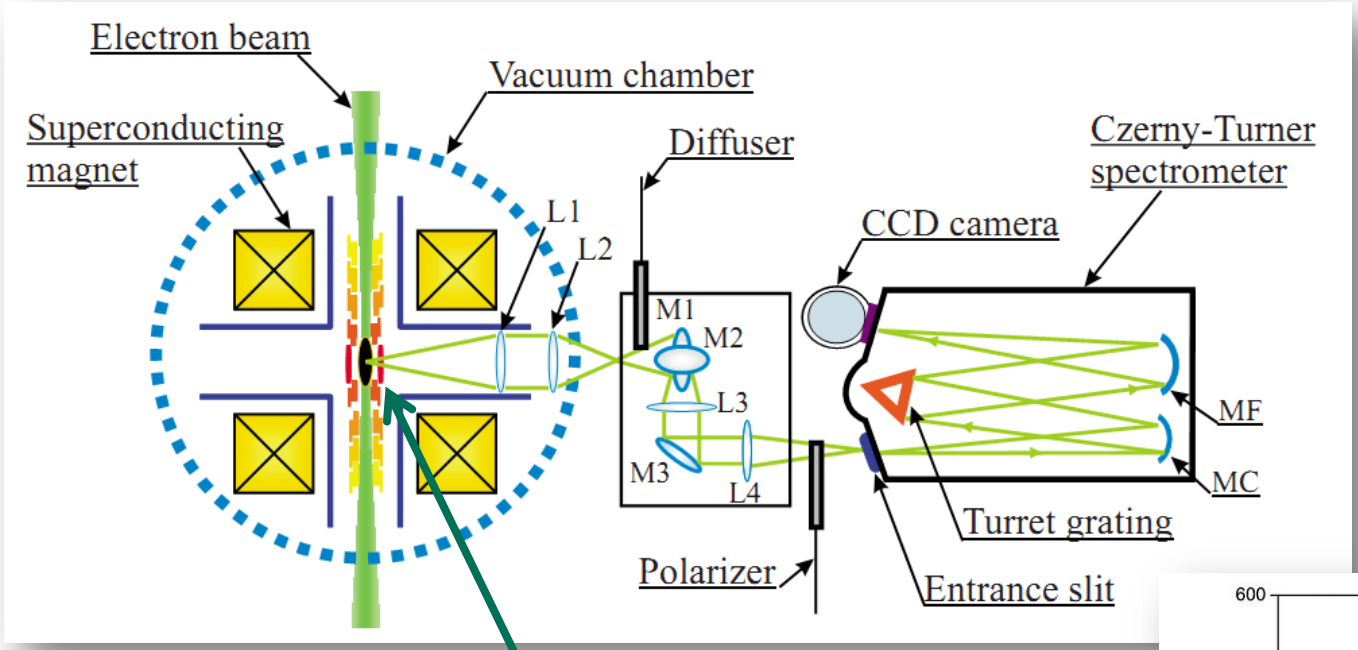
Accuracy of calculation: 6000 cm^{-1}

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

$\Delta q \approx 730{,}000\ cm^{-1}$

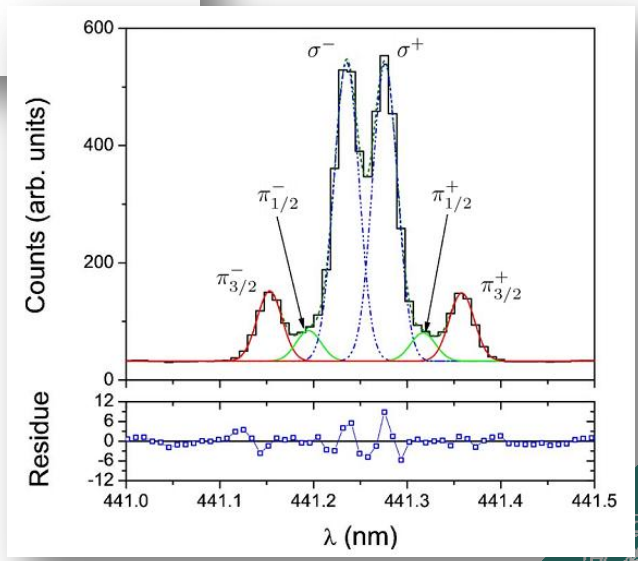
*Slide courtesy of P.O. Schmidt

EBIT fluorescence spectroscopy



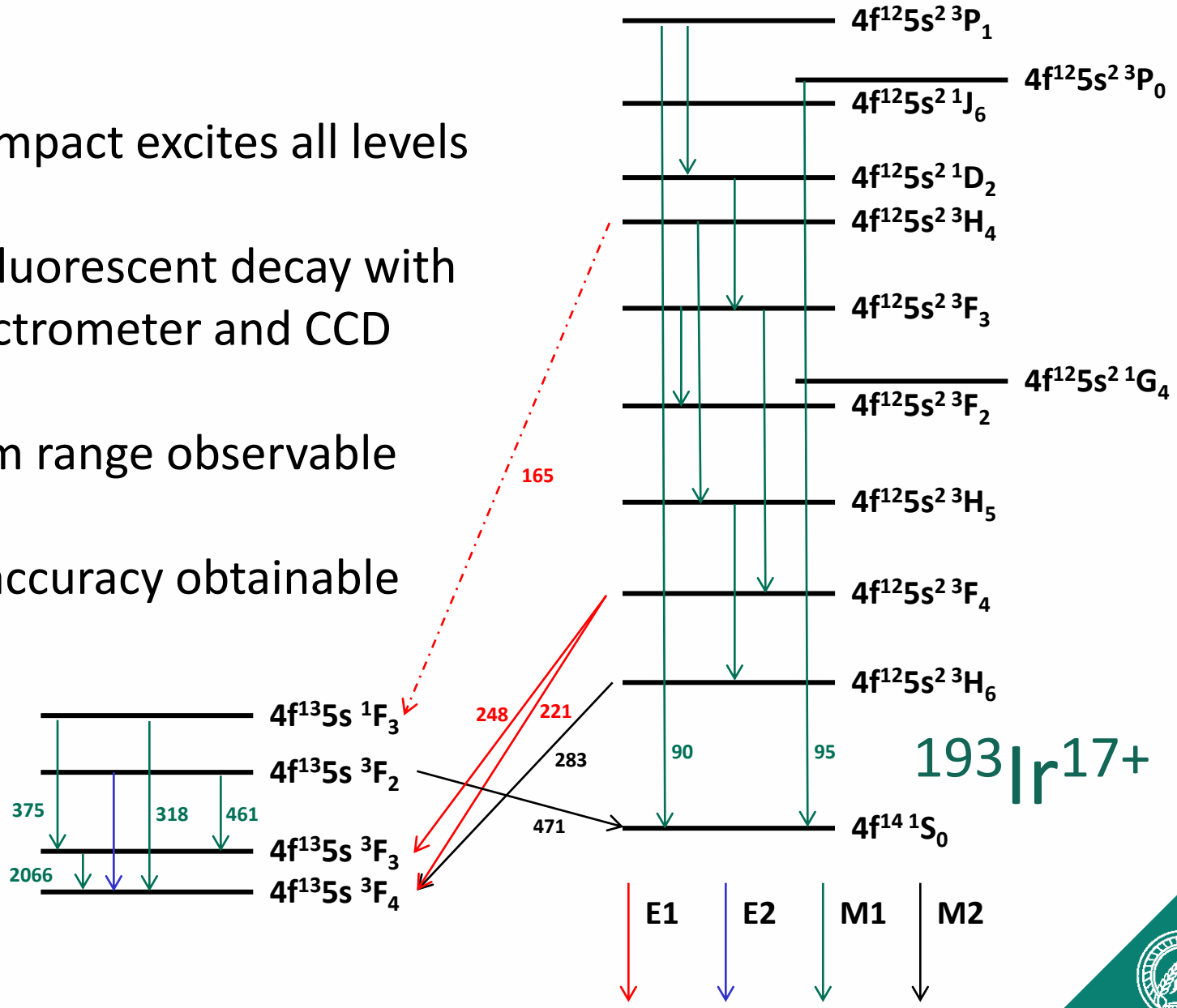
Orts et al., PRA 76, 052501 (2007)
Orts et al., PRL 97, 103002 (2006)

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



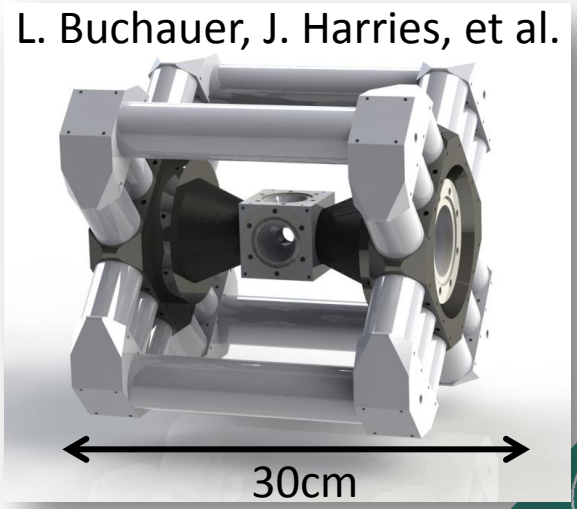
EBIT fluorescence spectroscopy

- Electron impact excites all levels
- Observe fluorescent decay with grating spectrometer and CCD
- 200-750nm range observable
- sub-ppm accuracy obtainable

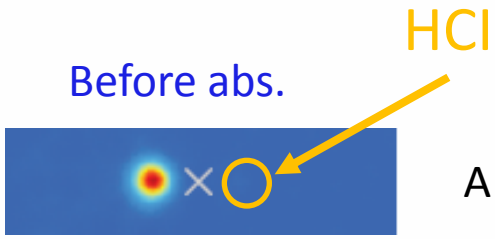


Summary & Outlook

- Highly charged ions for metrology and fundamental physics.
- Cryogenic Paul commissioned with MgH^+.
- Ir^{17+} excellent candidate. EBIT spectroscopy next months.
- Be+ cooling laser system operational. Construction of PI and spectroscopy lasers.
- Ongoing experiments in Aarhus; CryPTEx back at MPIK end of summer.
- Construction of small EBIT.

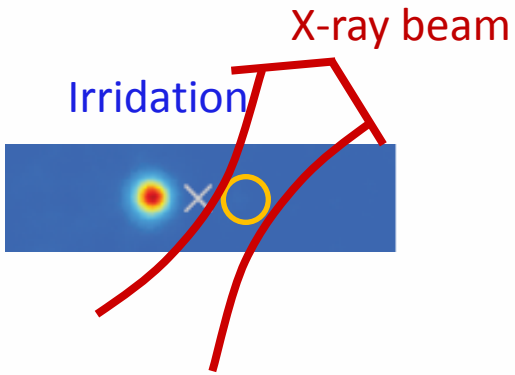


Single-Photon-Recoil-Induced-Melting-Spectrosopy (SPRIMS)*



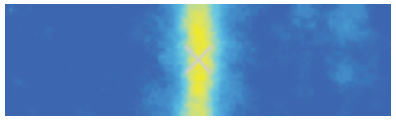
A two ion crystal: Be+ and a HCI

X-ray beam focused on HCI.
Absorption of hard photon



kinetic energy of ion
E_{photon} ~ 3 keV
$E_{kin,ion}=(E_{photon}^2)/(2m_{ion}c^2)=$
7.7×10^{-24} J = 0.56 K x k_B

After abs.



A two ion crystal will momentarily melt

→ Absorption can be detected from CCD-image with unit efficiency!

*Idea & slide concept: M. Drewsen

The crew & acknowledgements

Experiment\MPIK

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







Experiment\Aarhus University

- A. Hansen
- A. D. Gingell
- L. Klosowski
- M. Drewsen



Experiment\PTB

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

Funding

- MPG
- Aarhus University
- PTB
- COST-IOTA STSM