Investigating $\alpha$ 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
- Coulomb crystals
- Linear Paul trap design
- Molecular ions
- Quantum logic readout
- High-accuracy clocks
- Frequency comb
• Highly charged ions for metrology and fundamental physics
• Cryogenic Paul trap for sympathetic cooling of HCl ions
• Ir\textsuperscript{17+} and time variation of fine structure constant
• Outlook
Highly charged ions, scaling laws

• Ionization energy $\sim Z^2$

• Fine structure $\sim Z^4$

• Bohr radius $\sim Z^{-1}$; electron density at nucleus $\sim Z^3$

• Weak matrix element (parity violation) $\sim Z^5$

• QED contributions $\sim (Z\alpha)^n$
Laser spectroscopy of HClIs

\[
\text{Ar}^{13+} \text{ } ^2\!P_{3/2} - ^2\!P_{1/2} @ 441 \text{ nm by pulsed dye laser}
\]

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

Limited by Doppler line width! Need cooling...

K. Schnorr et al., in preparation
Sympathetic Cooling of HCl's

- RETRAP (LLNL):
  cryogenic Penning trap
  Be\(^+\) cools Xe\(^{34+}\)
  L. Gruber et al., PRL 86, 636 (2001)

- Proposals:
  M. Bussmann et al., Int. J. Mass Spectr. 251, 179 (2006)

- SPECTRAP @ GSI
  Resistive cooling &
  \(^{24}\)Mg\(^+\) ion cloud laser cooled in Penning trap
Sympathetic Cooling of HClIs

in a Paul trap

Coulomb crystal

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


2 single-ion Coulomb crystal

- Only 1 HCl 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
Cryogenic Paul Trap Experiments

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

Cryogenic Paul Trap Experiments

A cryogenic linear RF ion trap for sympathetic laser cooling of HCl ions 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 (Michael Drewsen’s Ion Trap group)
Experiments with cooled MgH+

intermezzo

Preparing externally and internally ultra-cold molecular ions
with the ion trap

Experiment with exciting results. Stay tuned...

Extr. and injection beamline*

Last week:
First extraction and deceleration!

*Slide by Lisa Schmöger
Be\(^+\) laser systems

Highly charged ions for metrology

- Strongly bound electrons
- Low susceptibility to certain external field shifts:
  - Second order Zeeman shift
    \[ \sim 1/Z_h^2 \text{ (BUT: linear shift } \sim \text{MHz/G)} \]
  - Stark shifts (BBR, light shift, trap induced, quadrupole)
    \[ \text{BBR } \sim 1/Z_a^4 \]
Variation of alpha

- Quasar absorption spectra
  - “Australian dipole” at 4σ
  - $\alpha/\alpha \sim 10^{-19}/\text{year}$
  - Webb et al., PRL 107, 191101 (2011)

- Hg+/Al+ Atomic clocks
  - $-1.6(2.3) \times 10^{-17}/\text{year}$
  - Rosenband et al., Science 319 (2008)
  - Need 100x improvement!
Highly charged ions for α-dot

Strong relativistic effects, enhanced sensitivity:

• High nuclear charge $Z$

• High ionization potential $I_n$

• Differences in the configuration composition (i.e. $\nu$, $j$)

• Scaling even faster with *hole transitions* $q \sim I_n^{3/2}$

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

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

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

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

Ir$^{17+}$

$q \sim 140,000 \text{ cm}^{-1}$

$q \sim 370,000 \text{ cm}^{-1}$

$q \sim 450,000 \text{ cm}^{-1}$

Compare: Hg$^+$ at

$q \sim 52,200 \text{ cm}^{-1}$

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

\( {^{193}\text{Ir}^{17+}} \) partial level structure

\[
\begin{array}{c}
4f^{13}5s^1F_3 \\
4f^{13}5s^3F_2 \\
4f^{13}5s^3F_4
\end{array}
\]

\[
\begin{array}{c}
4f^{12}5s^2^3F_4 \\
4f^{12}5s^2^3H_6
\end{array}
\]

\( q = 24,183 \text{ cm}^{-1} \)

\( q = -385,000 \text{ cm}^{-1} \)

\( q = -367,000 \text{ cm}^{-1} \)

\( \Delta q \approx 730,000 \text{ cm}^{-1} \)

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)

193Ir^{17+}
Electron impact excites all levels

Observe fluorescent decay with grating spectrometer and CCD

200 - 750 nm range observable

sub-ppm accuracy obtainable

$\text{Ti-like Ir}^{55+}$

Figure: Alex Windberger

EBIT fluorescence spectroscopy

$4f^{12}5s^2 3P_1$

$4f^{12}5s^2 3P_0$

$4f^{12}5s^2 1J_6$

$4f^{12}5s^2 1D_2$

$4f^{12}5s^2 3H_4$

$4f^{12}5s^2 3F_3$

$4f^{12}5s^2 3F_2$

$4f^{12}5s^2 1G_4$

$4f^{12}5s^2 3H_5$

$4f^{12}5s^2 3F_4$

$4f^{12}5s^2 3H_6$

$4f^{14} 1S_0$

193 $\text{Ir}^{17+}$
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.
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