# Laser Spectroscopy of Hyperfine Structure of the 1s Ground State of Highly Charged Ions

Richard Thompson

*QOLS Group, Blackett Laboratory,*
*Imperial College London*

# Outline of Talk

1. Introduction
2. Imperial College group
3. Why the interest in 1s ground state HFS?
4. Previous work
5. Experimental plans at HITRAP
6. Conclusion

# Imperial College Ion trap Group

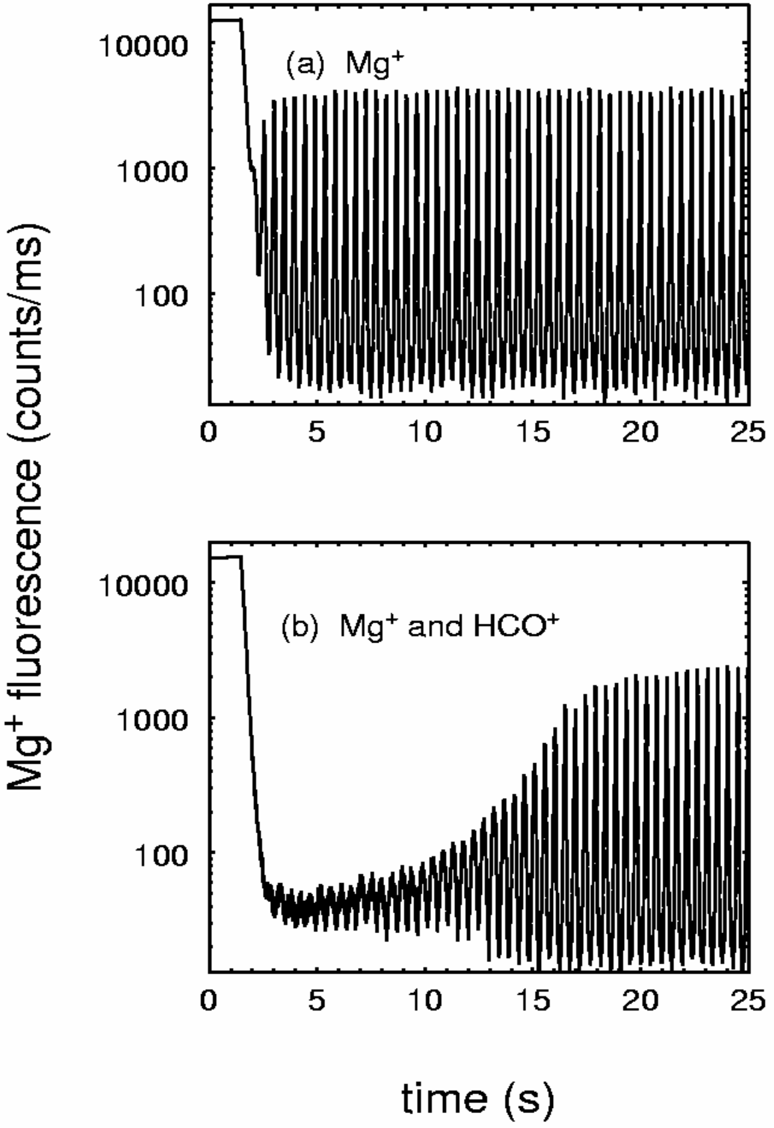
(R C Thompson, D M Segal, 2 RAs and 3 PhD students)

Our previous/current work in Penning traps includes:

- Laser cooling and spectroscopy of singly-charged ions
- Quantum jumps
- Dynamics of laser cooling and sympathetic cooling
- Axialisation of laser cooled ions
- Quantum Information Processing applications
- We have worked with $Be^+$, $Mg^+$ and $Ca^+$

# Sympathetic cooling

- Laser cooling only works for a few ion species
- Other species can be cooled via collisions with the laser-cooled ions
- This could allow the preparation of ultra-cold molecular ions or HCI
- The plot shows cooling of $HCO^+$ by laser-cooled $Mg^+$



# Axialisation

- With “buffer gas cooling” the magnetron motion in a Penning trap is *heated* by the collisions
- A weak radial quadrupole drive can be used to couple magnetron and cyclotron motions together so that cyclotron cooling dominates
- We decided to use this with *laser* cooling:

$$\dot{r}_c = \delta r_m - \gamma_c r_c$$

$$\dot{r}_m = -\delta r_c - \gamma_m r_m$$

  - $\delta$ is coupling rate
  - $\gamma_c$ is cyclotron cooling rate (large, +ve)
  - $\gamma_m$ is magnetron cooling rate (small, -ve)
  - Expect $r_c$, $r_m \Rightarrow 0$ for $t \Rightarrow \infty$

# Axialisation results

- We have recently built up a mathematical model of this process
- We find that the ions are strongly cooled provided that

$$\delta^2 > -\gamma_c \gamma_m$$

- Ions can be strongly cooled and tightly localised using axialisation

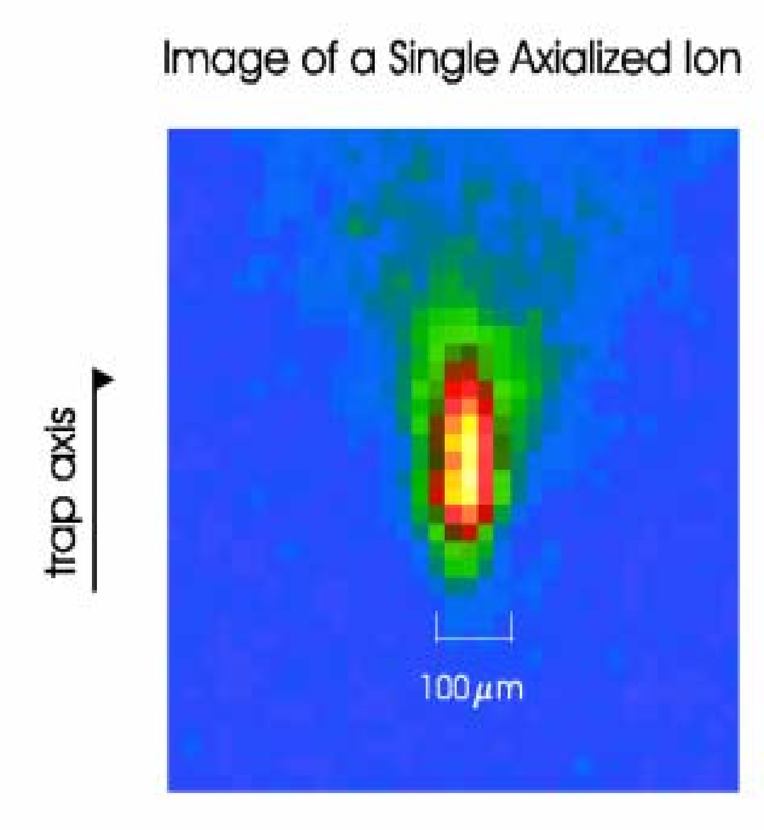


Image of a Single Axialized Ion

# Hyperfine Structure of H-like HCI

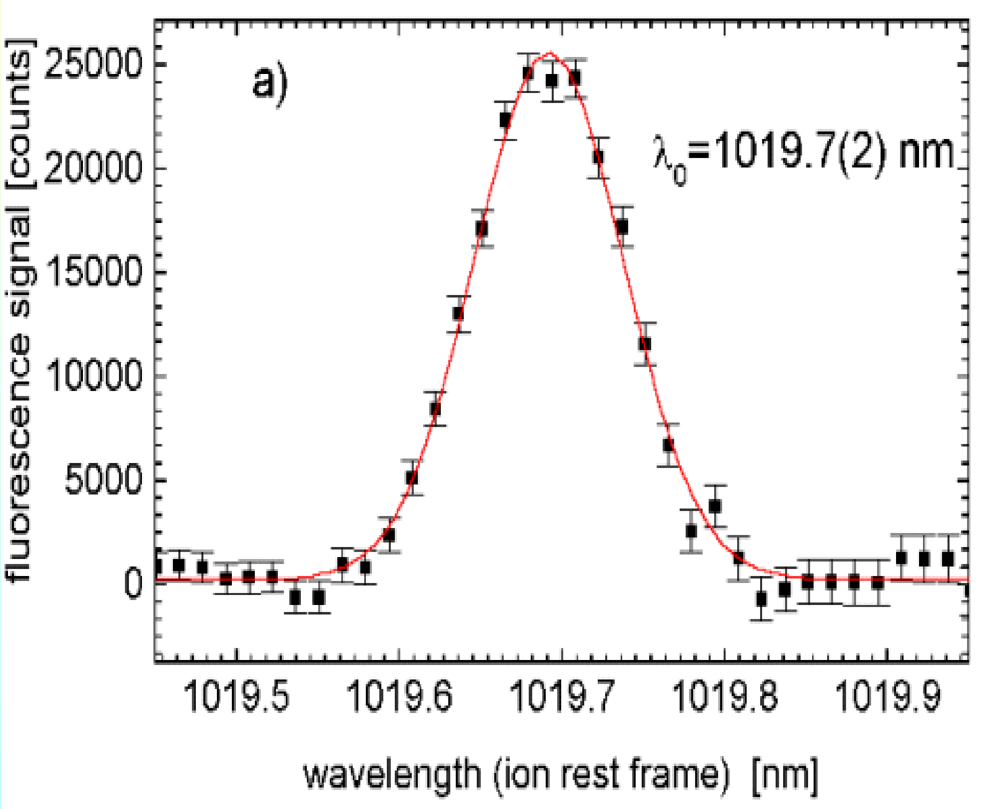
- In hydrogen the $1s_{1/2}$ ground state HFS is at 1400 MHz
- Frequency interval scales as $Z^3$ ; lifetime as $Z^{-9}$
- Around $Z$ ~ 70 the 1s HFS moves into the optical region
- M1 transition can be measured using laser spectroscopy
- A measurement can give information on:
  - Nuclear properties (charge and magnetisation distributions)
  - QED effects (vacuum polarization and self energy)
  - Later possibilities for optical pumping for weak interaction studies

# Previous work on 1s HFS

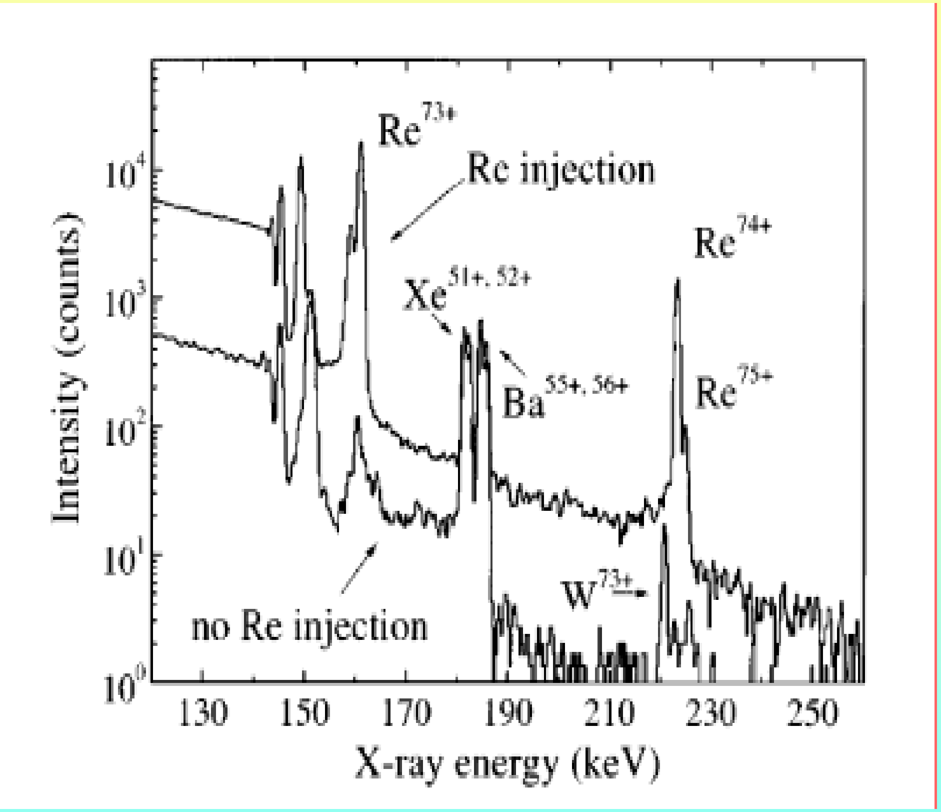
- Measurements in the ESR at GSI (laser excitation):
  - Bi ($Z$=83; $I$=9/2) $\lambda$=244nm; $\tau$=0.35ms (1994)
  - Pb (Z=82; $I$=1/2) $\lambda$=1020nm; $\tau$=50ms (1998)
- Measurements with Super-EBIT (emission spectroscopy):
  - Ho ($Z$=67; $I$=7/2) $\lambda$=573nm; (1996)
  - Re ($Z$=75; $I$=5/2) $\lambda$=456nm; (1998) [2 isotopes]
  - Th ($Z$=81; $I$=1/2) $\lambda$=386nm; (1998) [2 isotopes]
- RETRAP
  - HCI (Xe) loaded from EBIT into a Penning trap with sympathetic cooling from laser-cooled Be$^+$ ions (2001)
  - One possible use is for 1s HFS measurements

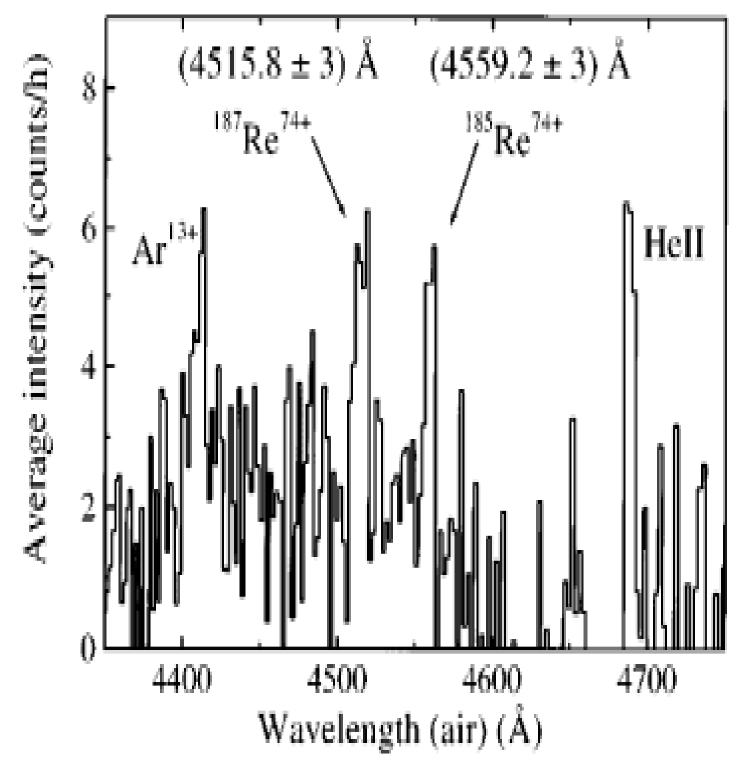
# GSI measurement of Pb

- Spectrum shows the ground state HFS transition in $^{207}\text{Pb}^{81+}$ at 1020 nm
- Measured in the ESR storage ring
- Accuracy is 0.2 nm ($2 \times 10^{-4}$)



# Super-EBIT measurement of Re





- X-ray fluorescence from the EBIT both with and without Re injection

- Optical fluorescence from Re in EBIT showing the M1 transition spontaneous emission

# Experimental plans with HITRAP

- Advantages of a measurement in HITRAP:
  - No calibration of beam velocity required
    - *Ions are at rest*
  - Cold ions have potentially narrower resonance
    - *Expect temperature around 4K*
  - Repeated measurements on a sample of ions
    - *Up to $10^5$ to $10^6$ ions expected*
  - Clean environment with efficient light collection
- Investigate optical pumping for polarisation of nuclear spin
  - Weak interaction studies possible

# Interpretation of Results

- Experiment yields the ground state HFS of the H-like ion
- The theoretical values include the following contributions:
  - Point nucleus HFS (Dirac)
  - Nuclear charge distribution correction (Breit-Schawlow)
  - Nuclear magnetisation distribution correction (Bohr-Weisskopf)
  - QED corrections
- At present uncertainty in the Bohr-Weisskopf correction due to core polarisation effects limits the comparison
- Combination with other measurements can eliminate this uncertainty
- Calculations are also continually improving

# Experimental Aspects

- Load ions into cryogenic Penning trap at 4K
- Use σ-polarised light to avoid undesired optical pumping
  - But slow beneficial optical pumping will occur for *F>0*
- Detect fluorescence at laser wavelength
- Scan laser across resonance to give spectrum
- Weak signal expected due to ~ms lifetime
- Optimise light collection efficiency
- Minimise background counts

# Practical points to consider

- Highly charged ions in the trap
  - Which ion?
  - Number of ions
  - Lifetime in trap
  - Temperature of ions
  - Further cooling?
  - Size of ion cloud
  - Doppler width

- Excitation of M1 transition
  - Availability of suitable laser
  - Power to saturate transition
  - Excitation rate achievable
  - Optical pumping of Zeeman states

- Detection of fluorescence
  - Pulsed or continuous?
  - Signal to background ratio
  - Width of resonance

# Rough Estimates of Experimental Parameters

- e.g. $^{207}Pb^{81+}$, $10^5$ ions at 4K (could be more)
- Thermal Doppler width at 4K for $\lambda$=1020 nm: 30 MHz
- Cloud size 0.5 mm
- 10 transitions per ion per second at saturation ($\tau$=50 ms)
- Laser power to saturate: 0.25 mW
- Quantum efficiency of collection and detection: 0.2%
- Maximum signal 2000 counts per second in cw mode
  - With background from scattered light
- If pulsed with 200 ms duty cycle, 1000 counts per second
  - With no scattered light background
- Resolution ~ $10^7$

# Conclusion

- There is significant interest in measuring HFS in the 1s ground state of high-*Z* highly charged ions
  - A unique testing ground for QED and nuclear structure theory
- Measurements in a Penning trap could have advantages over previous beam and EBIT measurements
  - Cleaner environment; cold ions; higher precision
- Also possibility for establishing polarisation of nuclear spin
- The experiment is exciting but also challenging:
  - Signal could be low
  - Stability and lifetime of ions in the trap
- Application for funds from UK research council pending