Precision Spectroscopy at SIS 200

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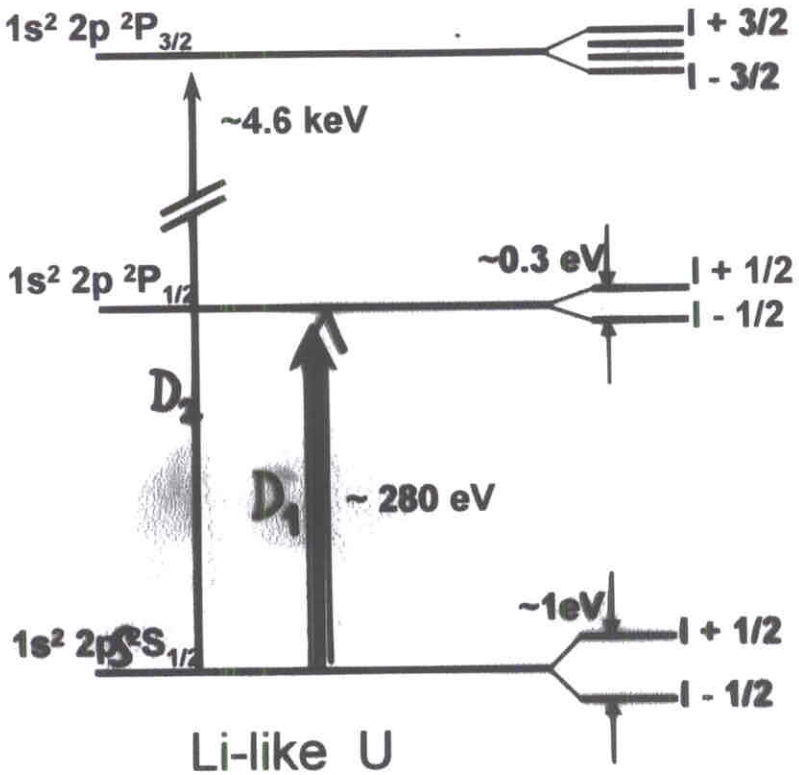
1. Precision Transition Energy Measurement at Li-like Heavy Ions by a Combined Collinear Laser and X-ray Spectroscopy
2. Hyperfine Spectroscopy and Polarization
3. Laser Cooling of Li-like Heavy Ions
4. Conclusion

1. Precision Transition Energy Measurement with

Collinear Laser Spectroscopy on Li-like heavy ions

(GSI Conceptual Design Report)



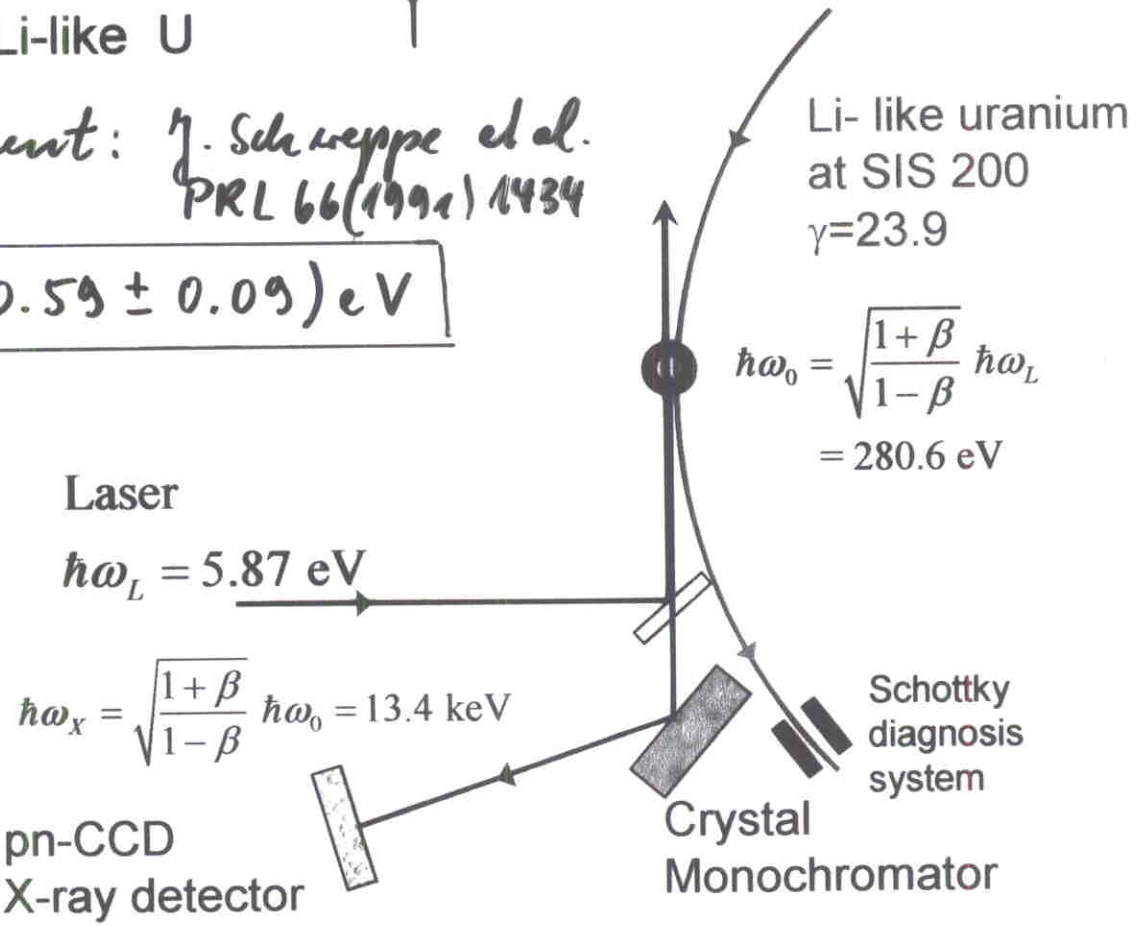
Li-like U

Excitation by

- **x-ray lasers and Doppler shift tuning at ESR or NESR**
- **conventional lasers at SIS 200**

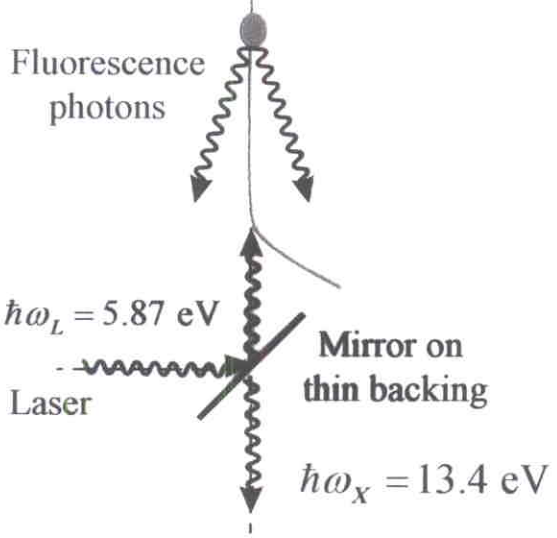
Experiment: J. Schweppe et al. PRL 66(1991) 1434

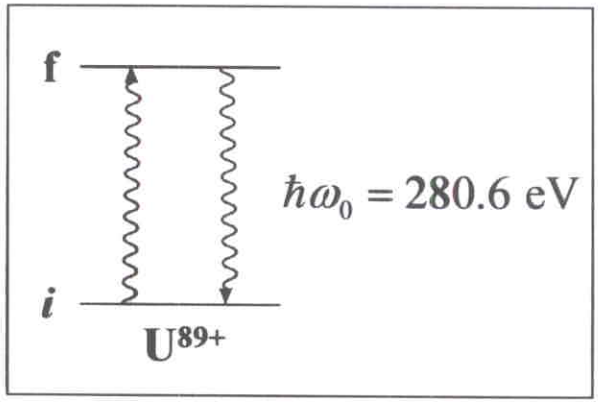
$E = (280.59 \pm 0.09)\,eV$



Principle of Experiment (U^{89+})

$$\beta = \frac{v}{c}; \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} = 23.9$$





Laser $$\hbar\omega_L = \sqrt{\frac{1-\beta}{1+\beta}} \cdot \hbar\omega_0 \underset{\gamma \gg 1}{\simeq} \frac{\hbar\omega_0}{2\gamma} = 5.87 \text{ eV}$$

Fluorescence $$\hbar\omega_X = \sqrt{\frac{1+\beta}{1-\beta}} \cdot \hbar\omega_0 \underset{\gamma \gg 1}{\simeq} 2\gamma \cdot \hbar\omega_0 = 13.4 \text{ keV}$$

Measurement of $\hbar\omega_L$ and $\hbar\omega_X$ in lab.system yields both

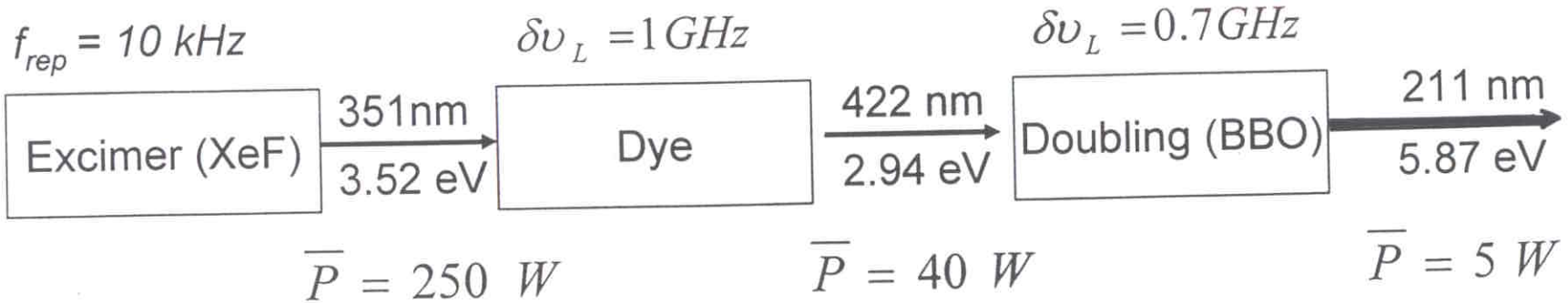
$$\hbar\omega_0 = \sqrt{\hbar\omega_L \cdot \hbar\omega_X}$$

and

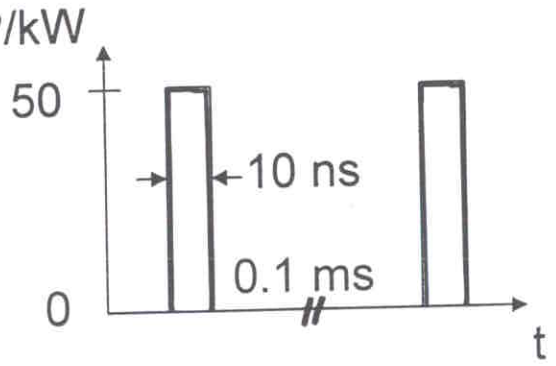
$$\gamma = \frac{1}{2}\sqrt{\frac{\hbar\omega_X}{\hbar\omega_L}}$$

The Laser System

As an Example



$$\frac{\delta\nu_L}{\nu_L} = 5 \cdot 10^{-7}$$

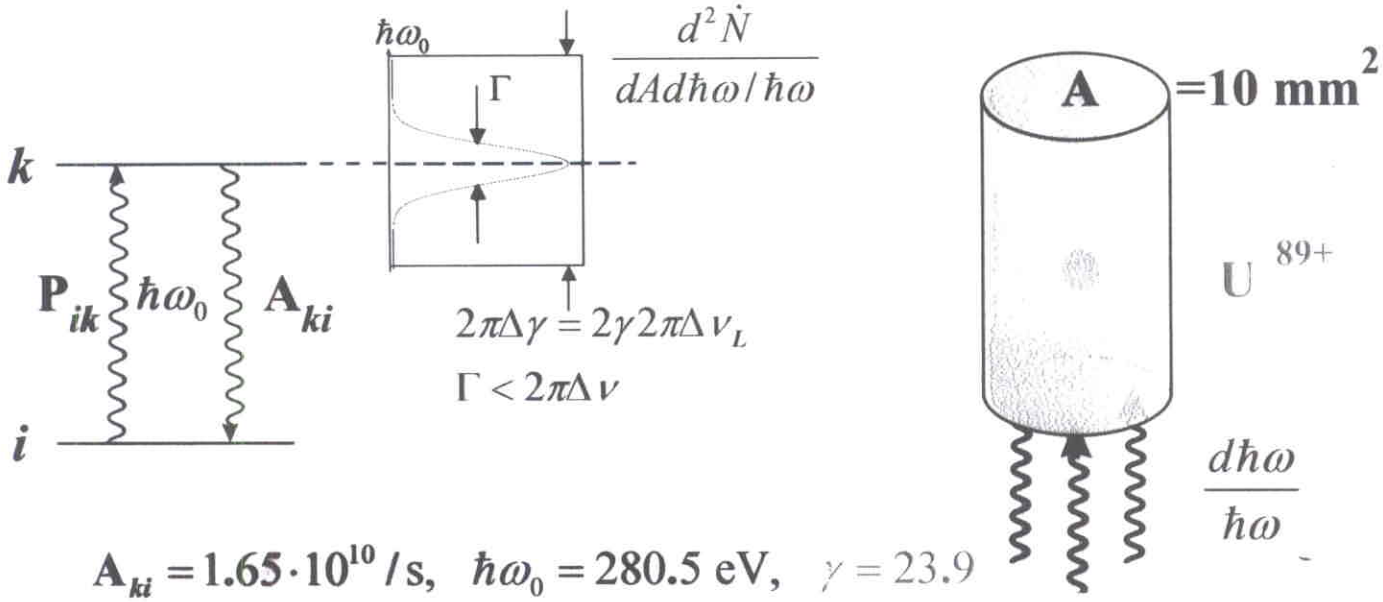


Spectral Photon Flux

$$\frac{d\overline{\dot{N}}}{d\nu_L/\nu_L} = \frac{5W}{5.87eV \cdot 5 \cdot 10^{-7}} = 1.1 \cdot 10^{25}\ /s$$

$$\frac{d\dot{N}_{puls}}{d\nu_L/\nu_L} = 1.1 \cdot 10^{29}\ /s$$

Fluorescence Rate (U^{89+})



$A_{ki} = 1.65 \cdot 10^{10}/\text{s}, \quad \hbar\omega_0 = 280.5 \text{ eV}, \quad \gamma = 23.9$

$$P_{ik} = \frac{d^2\dot{N}}{dAd\hbar\omega/\hbar\omega} \frac{A_{ki}}{\gamma} \frac{g_k}{g_i} \frac{\pi^2}{c} \left(\frac{\hbar c}{\hbar\omega_0}\right)^3$$

$\Gamma = 1.1 \cdot 10^{-5}$ eV, $\quad \Gamma/\hbar\omega_0 = 3.9 \cdot 10^{-8}$

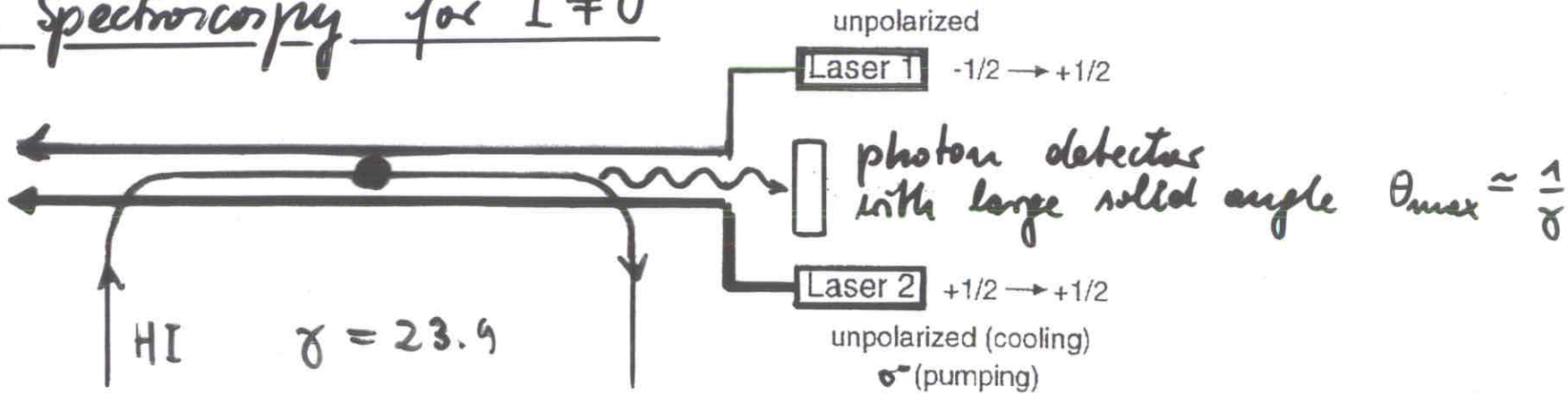
$$\frac{d^2\dot{N}}{dAd\hbar\omega/\hbar\omega} = \frac{1.1 \cdot 10^{28}}{\text{mm}^2\text{s}} \quad \textbf{for} \quad A = 10 \text{ mm}^2$$

Number of fluorescence photons

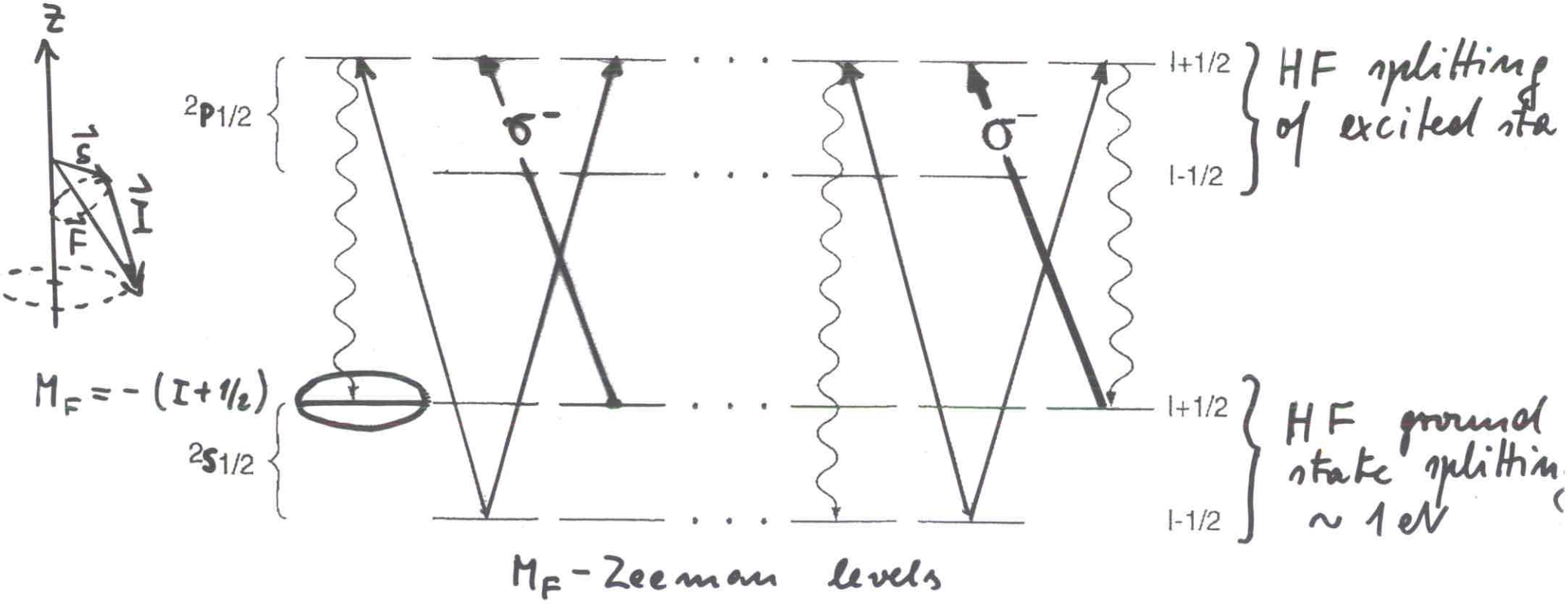
$$N_p = P_{ik}\Delta t_{puls} = \frac{1.1 \cdot 10^{28}}{\text{mm}^2\text{s}} \cdot \frac{1.9 \cdot 10^{-19}\text{mm}^2}{23.9} \cdot 10^{-8}\text{s}$$

$$N_p = 0.9/\,puls \quad \text{per ion}$$

· Hyperfine Spectroscopy for $I \neq 0$



and Polarization



Count Rate Estimate with large X-ray Detector

$$\dot{N}_X = \frac{(\Delta\nu/\nu)_{Laser}}{(\Delta\gamma/\gamma)_{H1}} (P_{ik}\,\Delta t_{pulse})\, f_{rep}\, N_{Li\text{-}like} \left(\frac{\Delta\Omega'}{4\pi}\right) \varepsilon_X$$

$$5\cdot 10^{-3} \cdot 1 \cdot 10^4/s \cdot 10 \cdot 0.01 \cdot 0.5$$

(not cooled)

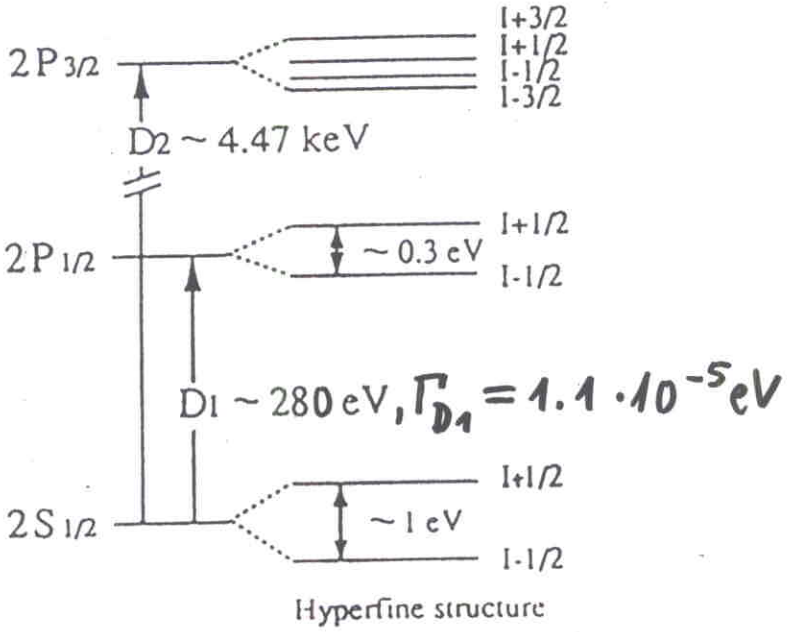
$$\boxed{\dot{N}_X = 2.5/s}$$ with 10 stored ions only

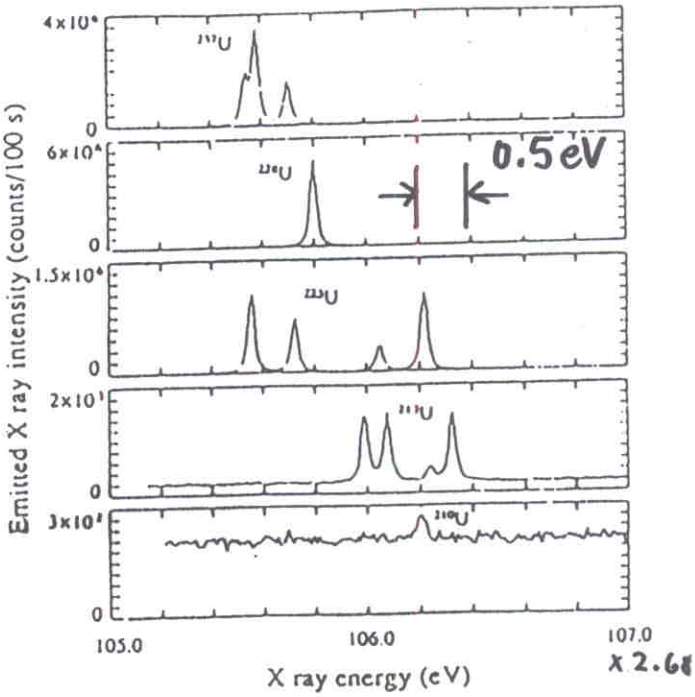
Line width without cooling

$$\frac{\Delta\hbar\omega_0}{\hbar\omega_0} = \frac{\Delta\gamma}{\gamma} \simeq 10^{-4} \;\Rightarrow\; \Delta\hbar\omega_0 \simeq 0.03\,eV$$

Future facility should allow for upgrades to reinject and accelerate Li-like spallation products

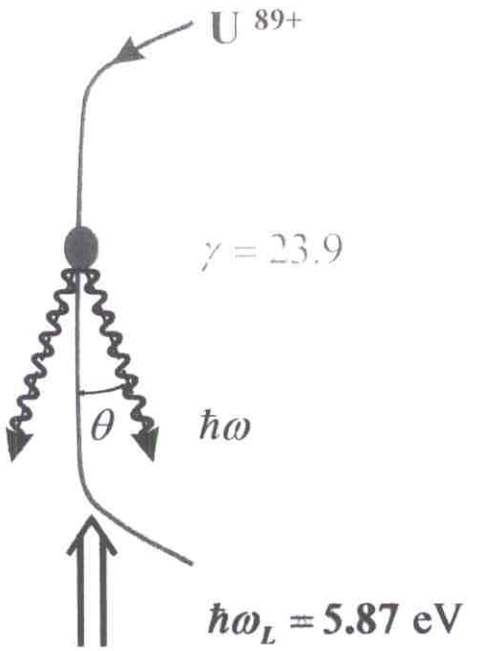
Isotope Shift (IS) and Hyperfine Structure (HFS) Measurements at Radioactive Beams





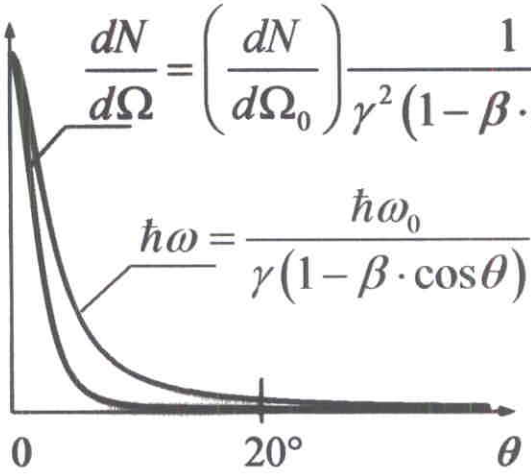
- In double-resonance experiments quite narrow line widths expected (≃3meV)
- Hyperfine fields can be calculated with high accuracy (compare with neutral atoms ΔIS≃10%, ΔHFS≃3%)
- IS shifts and magnetic moments can be measured for every elements, Q for Z≲45
- Very high sensitivity for any element (few radioactive ions sufficient)

Laser Cooling of HI Beam



$$\frac{dN}{d\Omega} = \left(\frac{dN}{d\Omega_0}\right)\frac{1}{\gamma^2\left(1-\beta\cdot\cos\theta\right)^2}$$

$$\hbar\omega = \frac{\hbar\omega_0}{\gamma\left(1-\beta\cdot\cos\theta\right)}$$



parallel momentum transfer to the HI $\overline{\delta p_{\parallel}} = \beta\gamma\hbar\omega_0 / c$

results in $\delta E_{HI} = \delta\gamma M_0 c^2 = \beta\gamma\hbar\omega_0$

$$\boxed{\frac{\delta\gamma}{\gamma} = \frac{\beta\hbar\omega_0}{M_0c^2} = 1.27\cdot10^{-9}}$$

Total energy shift $\frac{\Delta\gamma}{\gamma} = 10^{-4}$ **requires cooling time**

$$\boxed{\tau_c = \frac{\Delta\gamma/\gamma}{\delta\gamma/\gamma}\cdot\frac{1}{\left(P_{ik}\Delta t_{puls}\right)f_{rep}} = 8.7\ \text{s}}$$

Energy spread of HI bunch after cooling $\frac{\delta\gamma}{\gamma} = \left(\frac{\Delta\nu}{\nu}\right)_{\text{Laser}} = 5\cdot10$

can be improved further.

4. Conclusion

Laser Spectroscopy at SIS200 on Li-like Systems allow

- In combination with X-ray single crystal spectrometer precision transition energy measurements for QED tests
- Measurement of isotope shifts and magnetic moments at the D_1 transition for all elements
- Measurements of quadrupole moments for $Z \lesssim 45$ at the D_2 transition
- Laser cooling of heavy ion beams
- Preparation of polarized heavy ion beams (but many open questions)