Resonant Coherent Excitation of Relativistic Highly Charged Ions at Planar Channelling in Si-Crystals

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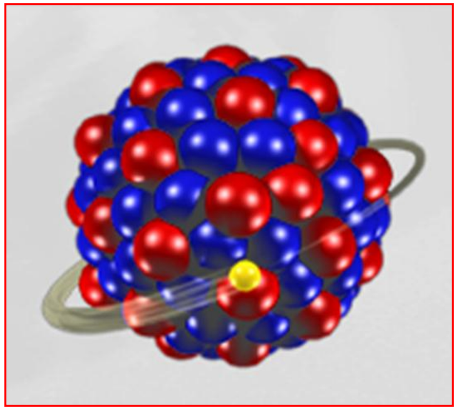
- Motivation
- Resonant Coherent Excitation (RCE)
- Experimental Setup at GSI
- Results
- Summary and Outlook

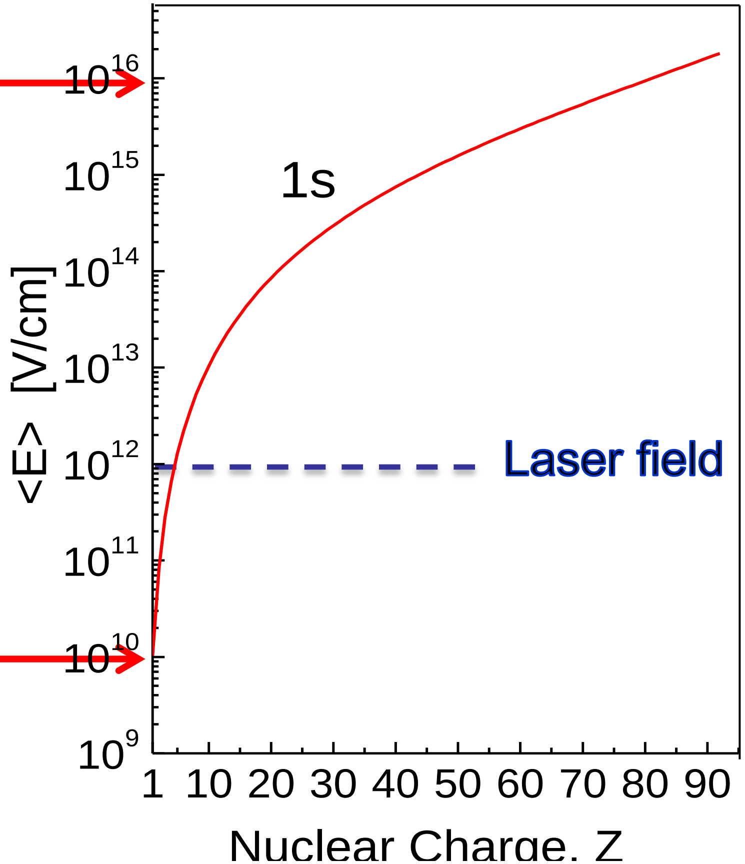
Motivation

Precision tests of QED in strong field of the heavy highly-charged ions

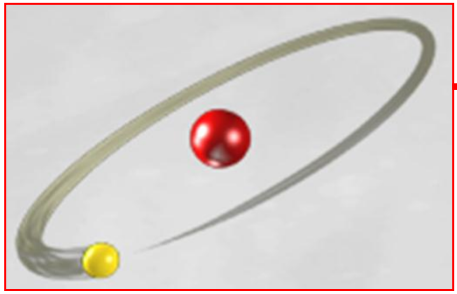
Uranium



Strong static electromagnetic fields: Z dependence of the field for the 1s electron



Hydrogen



$\Delta E \approx 500$ eV $Z\alpha \approx 1$

Quantum Electrodynamics effects

$\Delta E \approx 10^{-6}$ eV $Z\alpha \approx 10^{-2}$

GSI

Motivation

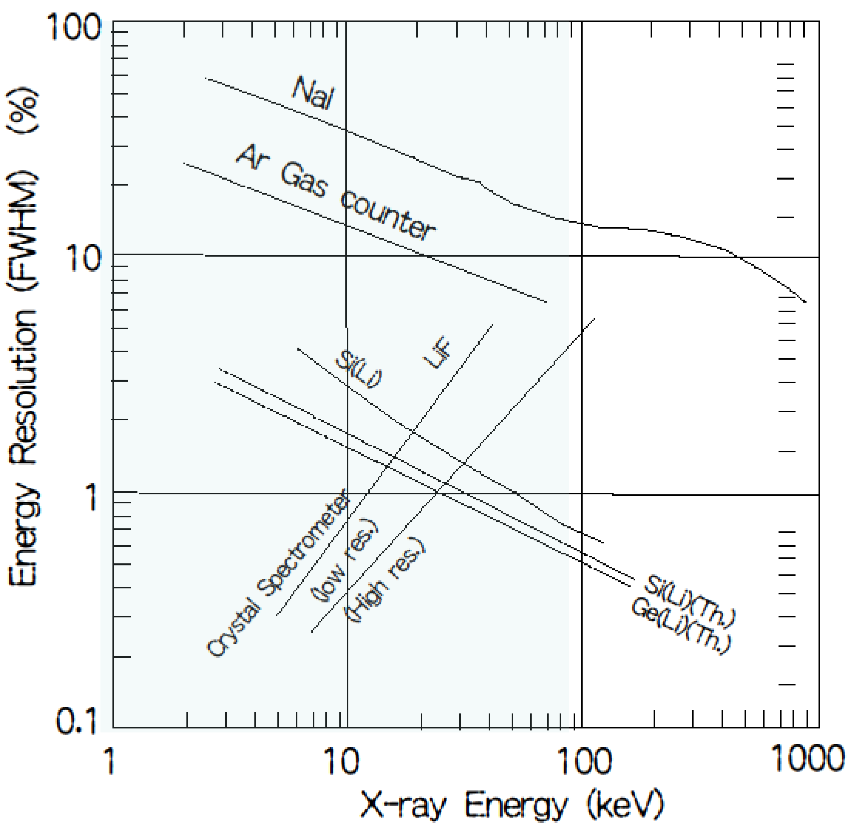
High precision energy measurements: tens of ppm

Direct measurements:

- Crystal spectrometers [1] E-Resolution Det.efficiency

Indirect measurements:

- Laser spectroscopy [2] E-Resolution soft X-rays
- Dielectronic Recombination [3] E-Resolution soft X-rays
- Resonant Coherent Excitation [4] ? E-resolution Det.efficiency



Range and Energy resolution of common x-ray detectors

Graph: c/o Y. Yamazaky

[1] P. Beiersdorfer – Phys.Rev.Lett. V 71 N24, 1993. – p. 3939-3942
[2] S.W. Epp et.al., Phys. Rev. lett. 98, 1830001 (2007)
[3] C. Brandau et al., Phys. Rev. lett. 91, 0732021(2003)
[4] K. Komaki et al., NIM B 146 (1998) 19-28

Motivation

- **Observation of RCE of the heaviest stable ion**

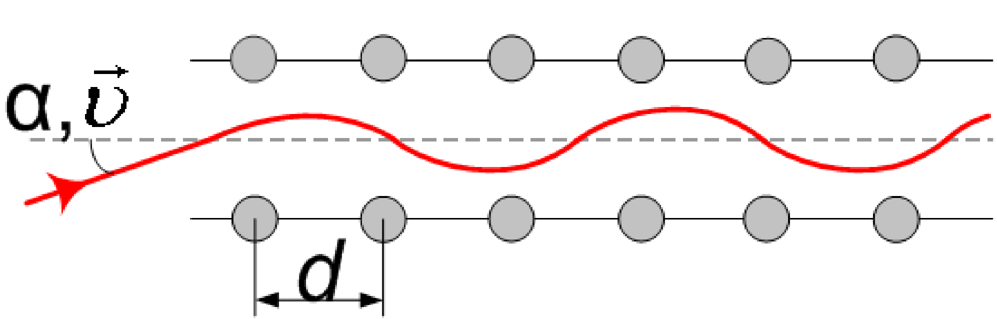
$$E \sim - \frac{z^2}{n^2}$$

	Excitation energy	Projectile energy
Atomic RCE	<10 keV	0.1 - 2 GeV/u (GSI today)
Nuclear RCE	~ 10 keV and higher	10 - 30 GeV/u (FAIR future)

- **To investigate the limits of the coherent excitation as possible spectroscopic method**

Resonant Coherent Excitation

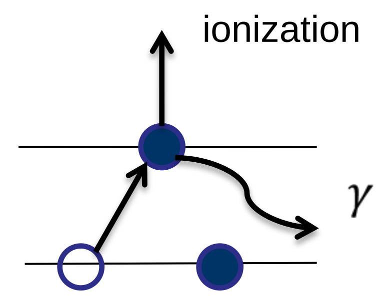
Planar channeling motion in a crystal



$$\nu_{field} = \gamma\, k\, \frac{\vec{v}}{d};\ k = 1,2,3,\ldots$$

$$\nu_{tr} = \Delta E / h = E_{n,l} - E_{n_0,l_0}$$

$$\nu_{field} = \nu_{tr} \longrightarrow \textbf{RCE}$$



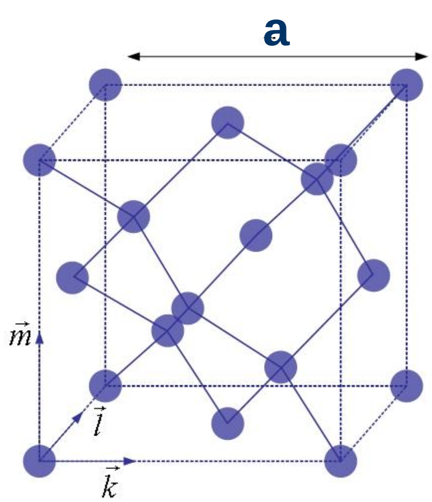
RCE → **De-excitation** → **Ionization**; **Photoemission** $\nu_\gamma = \Delta E_{ij} / h$

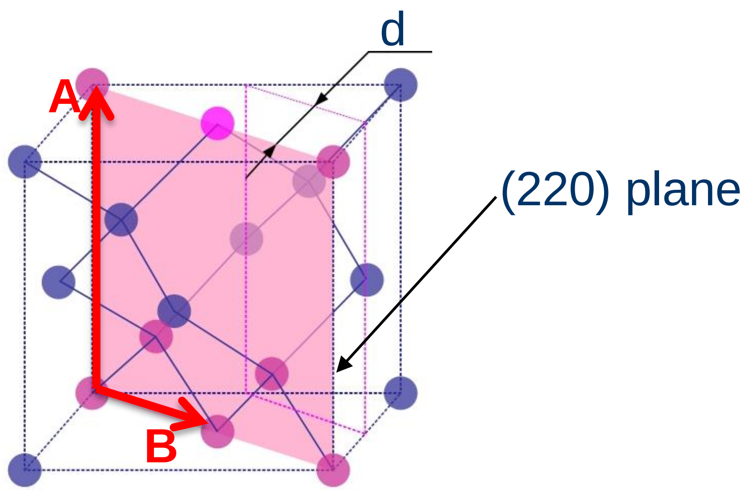
- Okorokov predicted and pointed first time RCE [1]
- Datz made the first experimental confirmation of RCE (with light ions) [2]
- RCE observation with middle heavy ions [3]

[5] V.V. Okorokov, Yad. Fiz. 2 (1965) 1009 [Sov. J. Nucl. Phys. 2, (1966) 719]
[6] S. Datz et al, Phys. Rev. Lett. 40 (1978)
[4] K. Komaki et al., NIM B 146 (1998) 19-28

Face centered cubic structure

$$a = 5.4\,\text{Å}$$





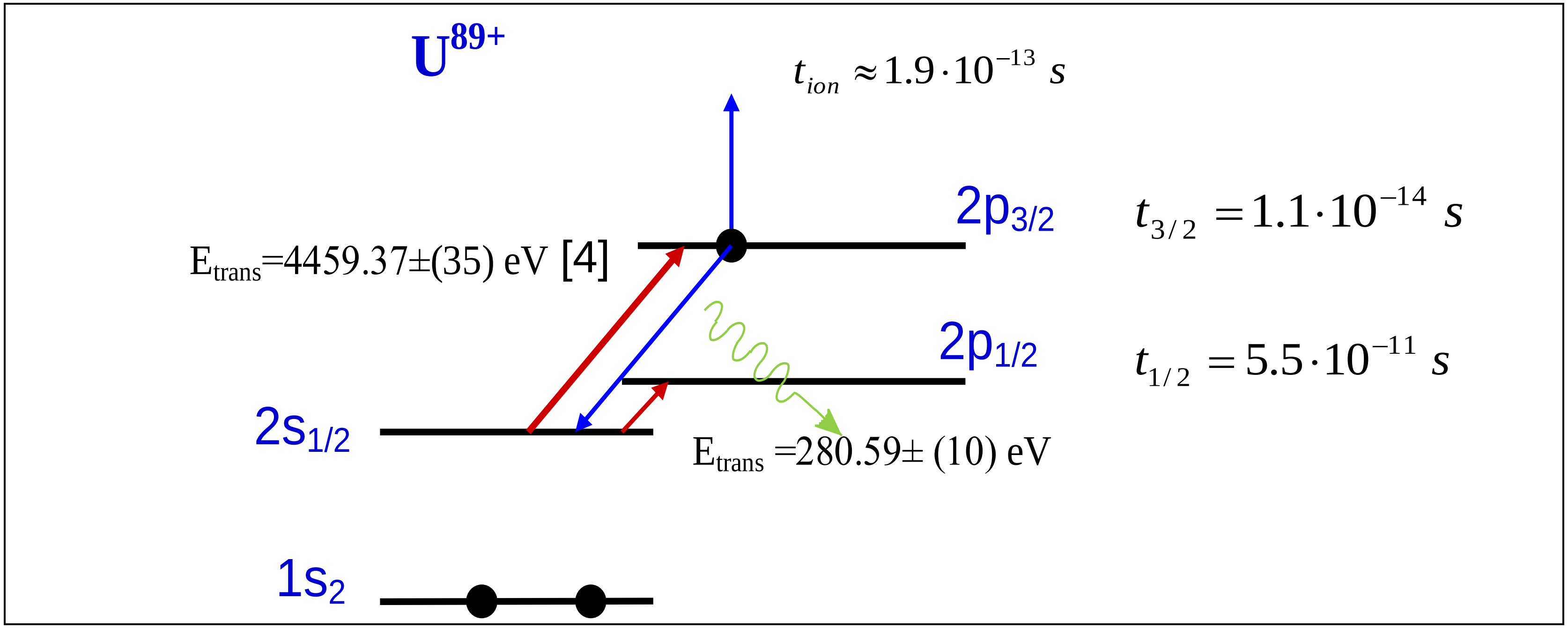
Frequency of the oscillating crystal potential $\nu_{field} = \gamma\langle\vec{g}.\vec{\upsilon}\rangle$

Transition energy $E_{tr} = h\nu_{field} = \gamma h\vec{v}(k\cos\theta/A + l\,\sin\theta/B)$

$$A = \frac{a}{\sqrt{2}};\mathrm{B} = \mathrm{a}$$

Resonant Coherent Excitation of Li-like U

Atomic Level Scheme of Li-like U



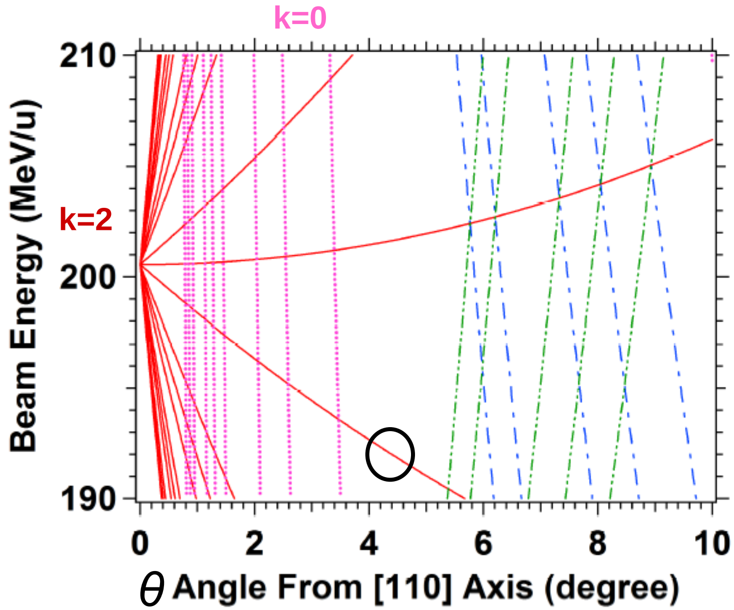
$$2P_{3/2} \rightarrow 2S_{1/2}$$

[1] P. Beiersdorfer – Phys.Rev.Lett. V 71 N24, 1993. – p. 3939-3942

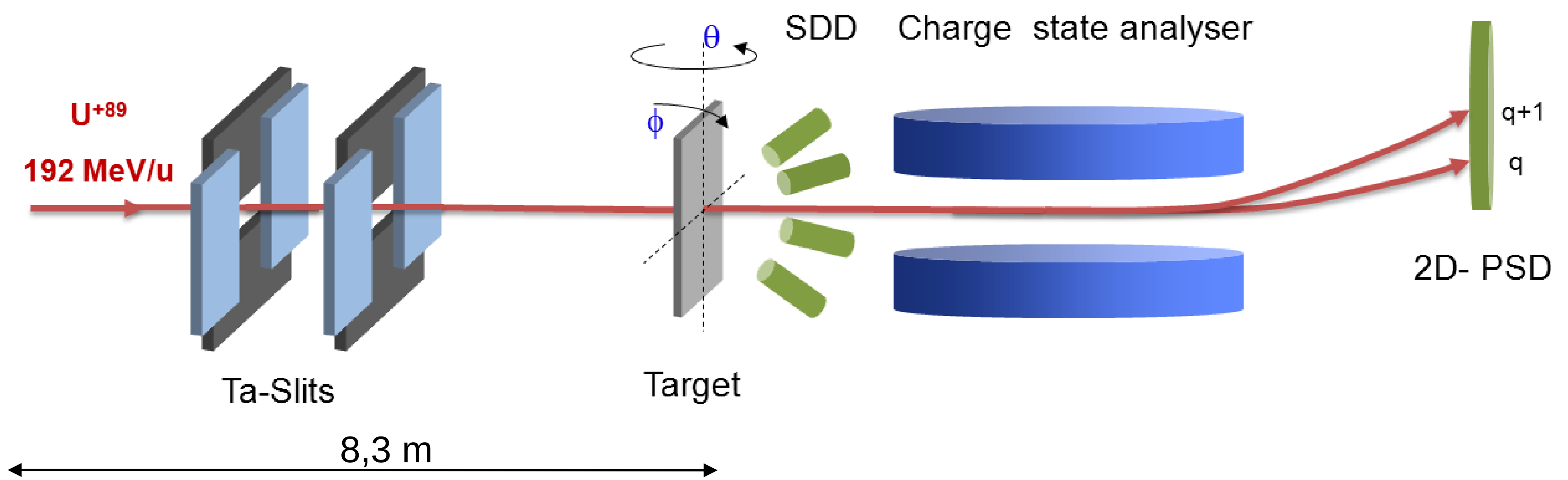
Experimental parameters

Transition energy $E_{tr} = h\nu_{field} = \gamma h\vec{v}(k cos\theta/A + l\, sin\theta/B)$

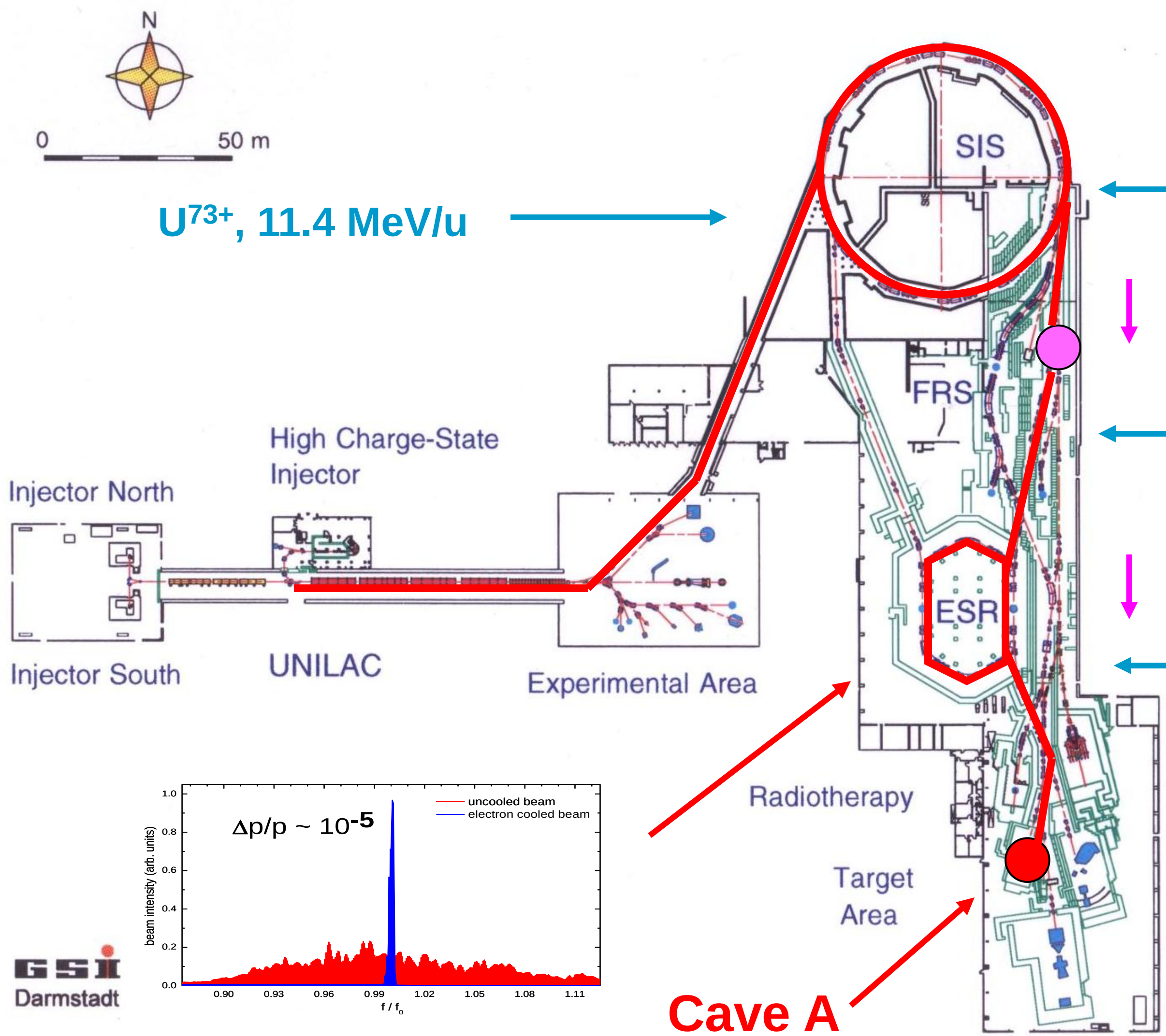
- **Beam energy** $E = 192\ MeV/u$
- **Miller indexes** $k = 2, l = 1$
- **Ion incident angle relatively to the target** $\theta = 4{,}7°$



Cave A – Setup Exp S351



Beam preparation



Extraction from SIS U^{73+} 193 MeV/u

Stripping, Cu 20 mg/cm²

Injection into ESR U^{90+} E_{ion} ~192 MeV/u

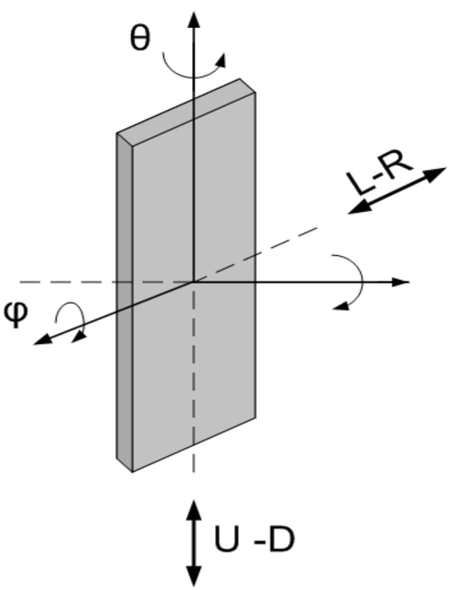
e-cooling at 191.2 MeV/u

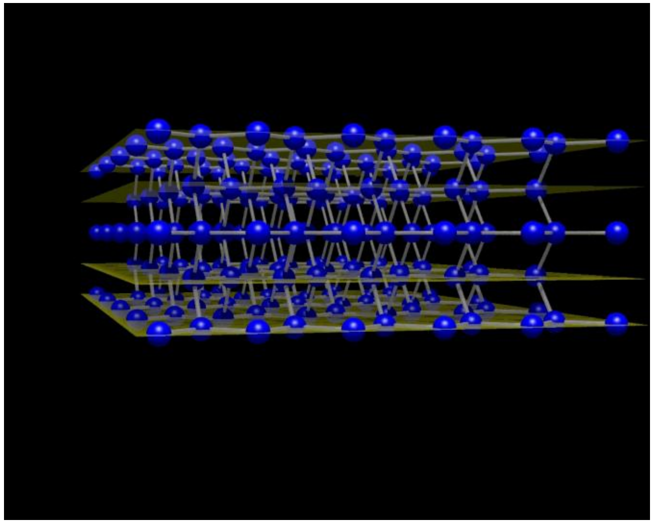
Slow beam extraction by charge exchange in the e-cooler of $U^{90+} \rightarrow U^{89+}$

GSI Darmstadt

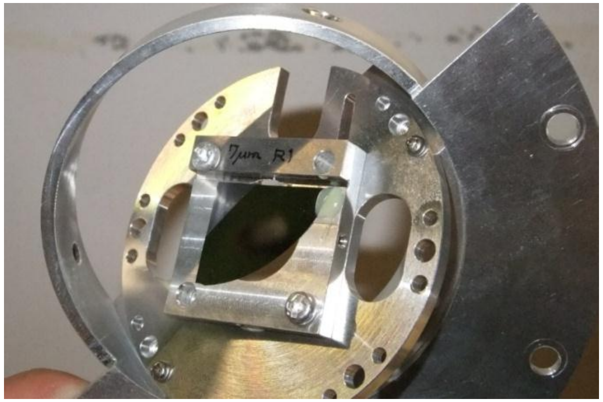
Target

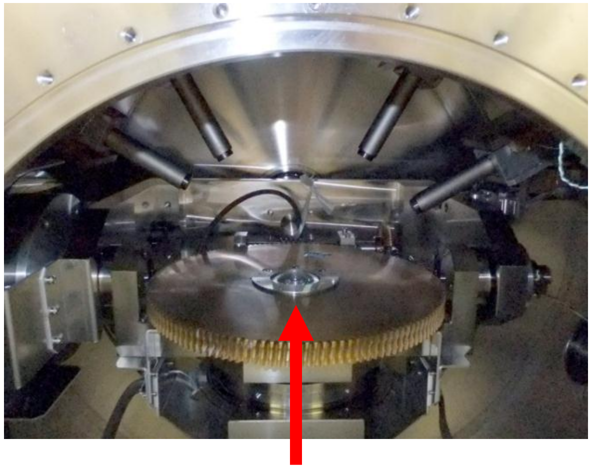
Si-crystal: **7 μm thickness**
100 mm^2 area





Rotation with a step of $\theta = 0{,}02°$





ion beam

Alignment of the target along 2 direction and rotation around 3 axis

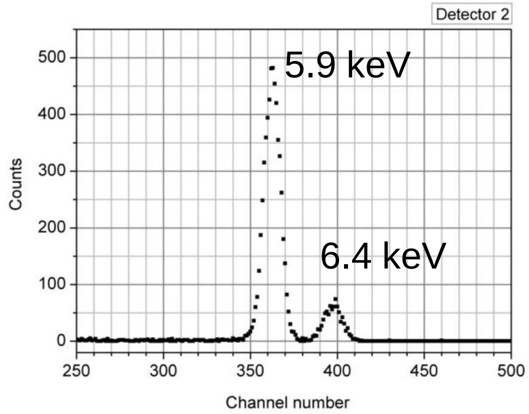
Detectors

X-rays detection

The Silicon Drift Detectors (SDD) [5]

- 80 mm^2 active area
- 450 µm thickness
- $\varepsilon = \sim 99\%$ for $E\gamma$= 5.9 keV
- Solid angle ~ $4.7 \cdot 10^{-3}$
- Reset-type low noise preamplifier
- Peltier cooling system (+20°C)
- Vacuum compatible

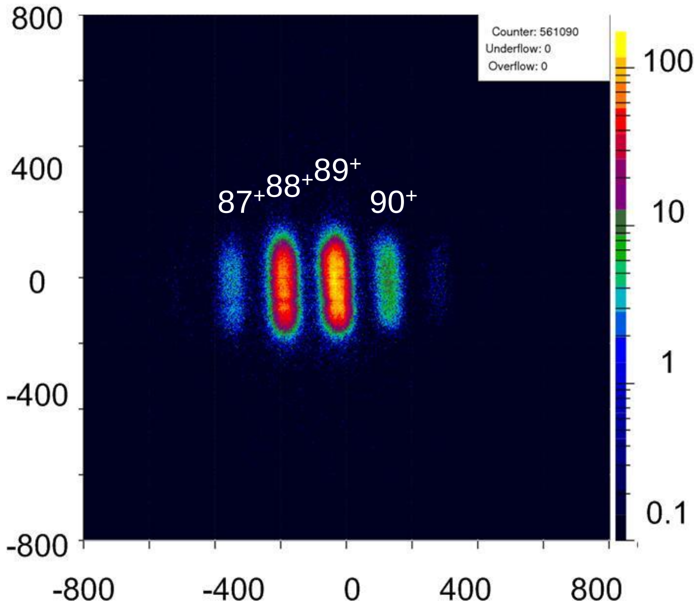
Calibration Fe^{55} FWHM = 190 eV @ 5.9 keV



Ions detection

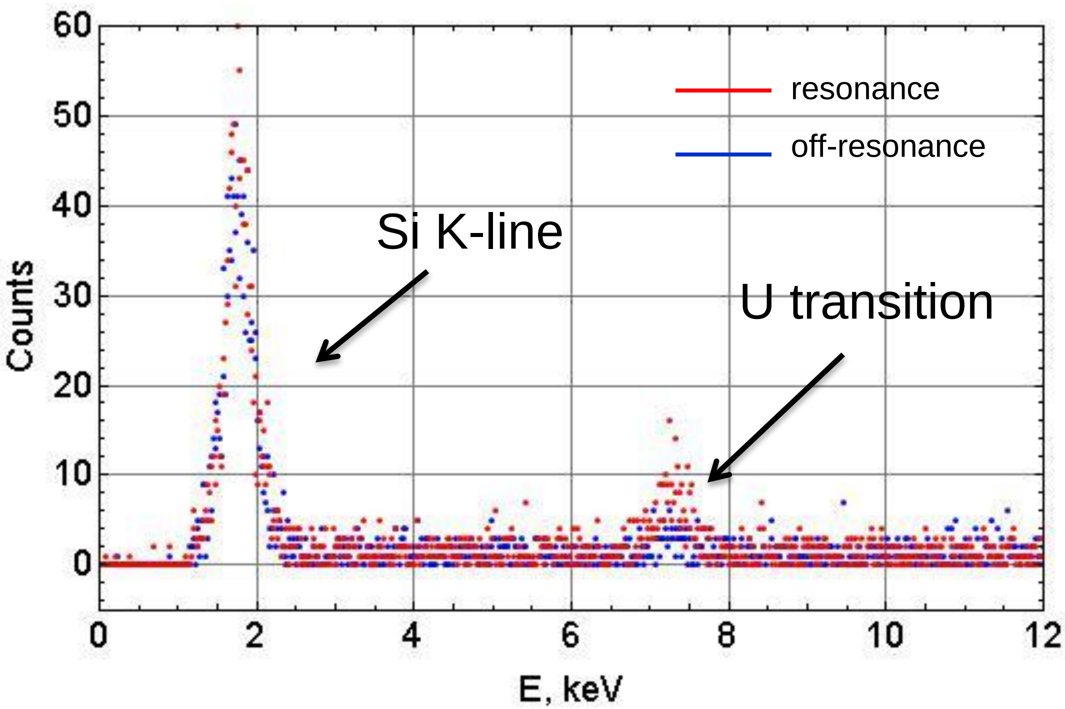
2D Position Sensitive MCP Detector

- Chevron configuration
- Read-out: Delay line
- Ø 75 mm
- Position resolution < 0.5 mm
- 100% detection efficiency, rate dependent



[7] KETEK GmbH, Germany URL: http://ketek.net

X-Ray Spectra



Doppler transformation

$$E_{lab} = \frac{E_\gamma}{\gamma\left(1 - \beta\cos\theta_d\right)}$$

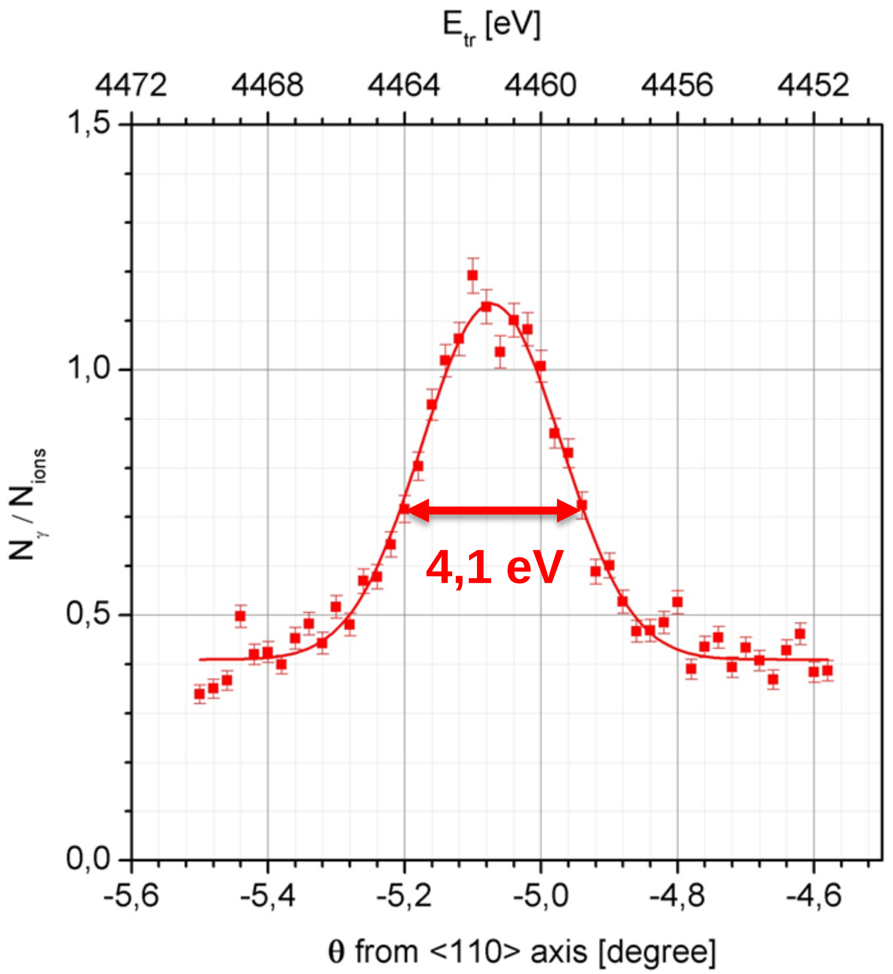
$$\theta_d = \pm 33°$$

$$E_\gamma = 4570.8\ eV$$

X-ray emitted by *191.2 MeV/u* U^{89+} ions resonant excited in the Si-crystal in the (220) planar orientation.

FWHM ~ 200 eV @ 7,1 keV $\frac{\Delta E}{E} \approx 10^{-2}$

Resonance curve



Photon yield dependence on the incident ion angle

$$\theta = -5.07^{\circ}$$

$$E_{tr} = \frac{h\gamma v}{a}\left(\sqrt{2}\, k\, cos\theta + l\, sin\theta\right)$$

	E_{γ}, eV	FWHM, eV
RCE method	4461.11±1 eV	4.1
Cryst. sp. [5]	4459.37(21)±0.25	2.1

$$\frac{\Delta E}{E} \approx 10^{-3}$$

[1] P. Beiersdorfer – Phys.Rev.Lett. V 71 N24, 1993. – p. 3939-3942

Transition Energy and Resonance width

	ESR experiment
Transition energy	4461.11±1 eV
FWHM	4.1 eV

- **Natural width of the resonance ~ 10^{-6}**

Experimental parameters	**Value**	**Contribution to FWHM**
	ESR experiment	
Momentum distribution	4×10^{-5}	0.3 eV
Energy loss	0.15 MeV/u	1.9 eV
Energy straggling	0.008 MeV/u	0.2 eV
Angular straggling	0.16 mrad	0.06 eV
Beam divergence	1.4÷4.5 mrad	1.6÷4.8 eV

[8] Y. Nakano et al., to be submitted

Summary and Outlook

- RCE of Li-like relativistic U have been detected with a count rate of 7 photons per second
- The transition energy E_{tr} = 4461.11±1 eV of $2p_{3/2}$-$2s_{1/2}$ in U^{89+} was defined with energy resolution of 10^{-3}

To improve the precision

- Better control on the beam divergence
- Better control on the energy loss: a new measurement with a thinner target

To investigate the anisotropy of the radiation

Thank you for your attention!