Observation of Double Resonant Coherent Excitation of Highly-Charged Ions in Crystals

Content

- **Motivation**
- **Resonant Coherent Excitation:**
  Single and Double RCE
- **Experiment**
- **Summary and Outlook**

Collaboration

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HGS-HIRe for FAIR

Motivation

Goal:

To observe Double RCE in highly-charged ions at non-channeling conditions

- **Okorokov predicted and pointed first time RCE in 1966** [1]
- **Datz made the first experimental confirmation of RCE in 1978** [2]
- **Further studies of RCE after 1996** [3]

Today:

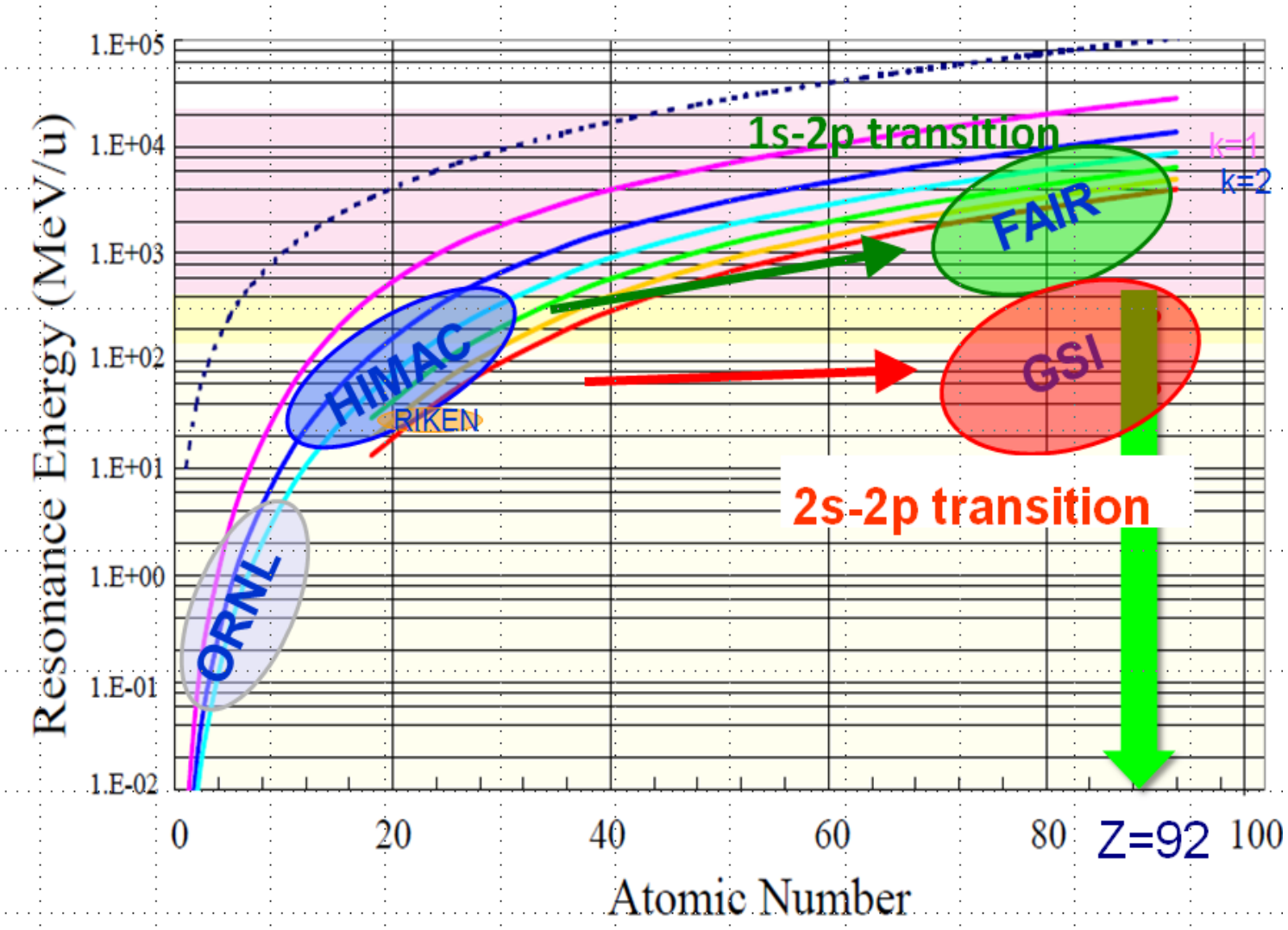
- **Atomic RCE in Ar (inter-shell, < 10 keV) : E_{beam} = 100 - 800 MeV/u (HIMAC)**
- **Atomic RCE in U (intra-shell, < 10 keV) : E_{beam} = 100 - 400 MeV/u (GSI)**

Future:

- **Atomic and Nuclear RCE (~ 100 keV) : E_{beam} < 10 GeV/u (FAIR)**

[1] V.V. Okorokov, Yad. Fiz. 2 (1965) 1009 [Sov. J. Nucl. Phys. 2, (1966) 719]
[2] S. Datz et al, Phys. Rev. Lett. 40 (1978)
[3] C. Kondo, Y. Nakano, T. Azuma, K. Komaki, Phys. Rev. Lett. 97 (2006)

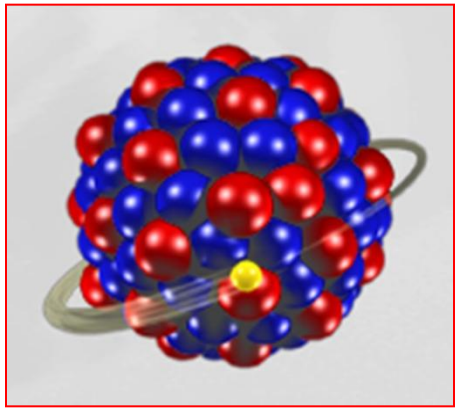
Motivation


Resonance Energy (MeV/u)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
0
20
40
60
80
100
Atomic Number
1s-2p transition
k=1
k=2
FAIR
GSI
HIMAC
RIKEN
ORNL
2s-2p transition
Z=92

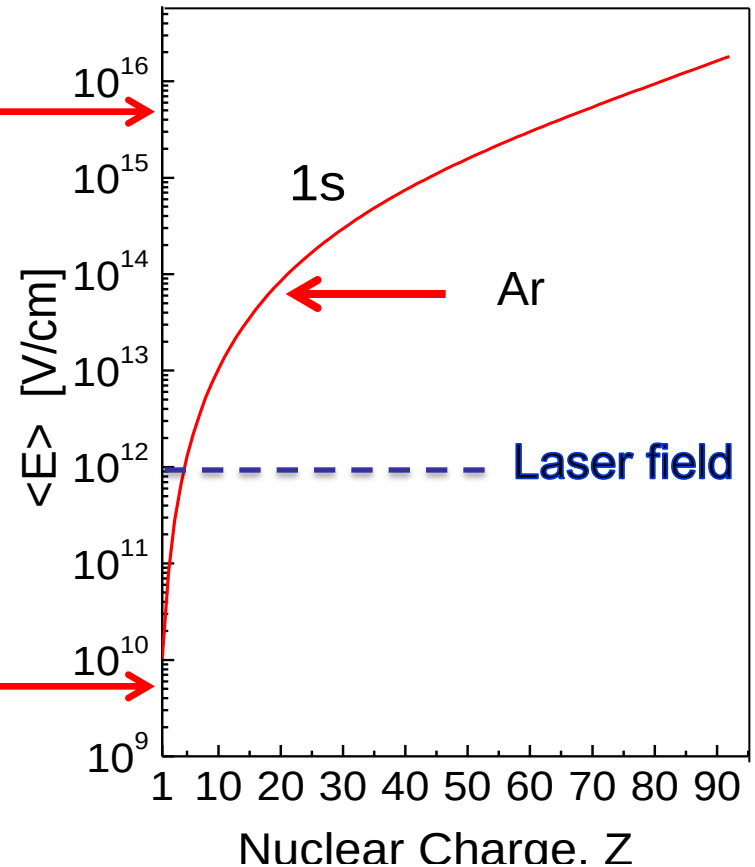
Motivation

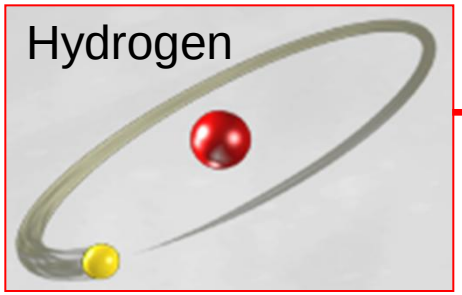
Precision tests of QED in strong field of the heavy highly-charged ions

Uranium



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





Ion-atom interaction

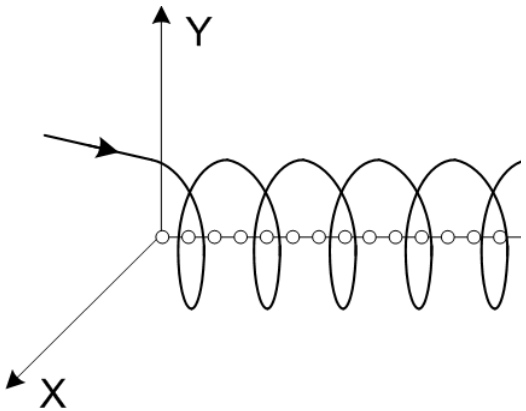
Ion + atom

- Electron capture
- Ionization
- Excitation

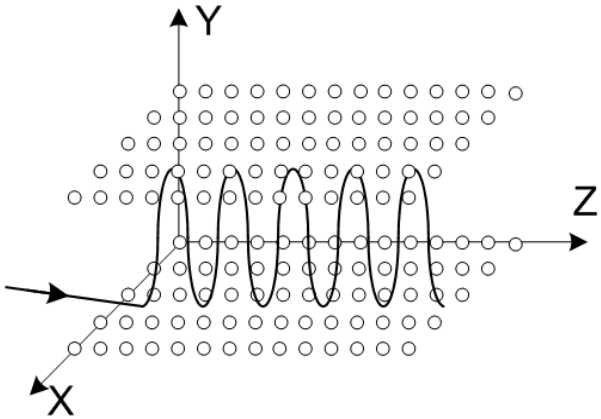
Excitation → De-excitation → Ionization / Photoemission

Ion motion in a crystal

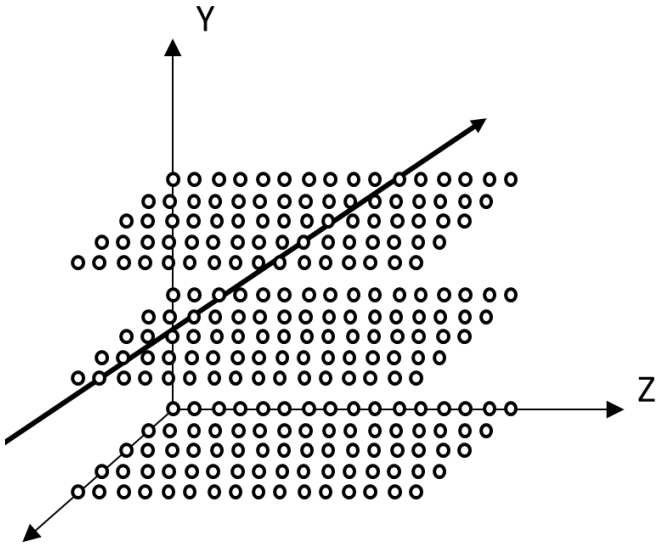
Crystal field: $$\vec{\phi}(r) = \sum_n \vec{\phi}_{\vec{g}} \exp\left(2\pi i \vec{g} \cdot \vec{r}\right)$$



Axial channeling

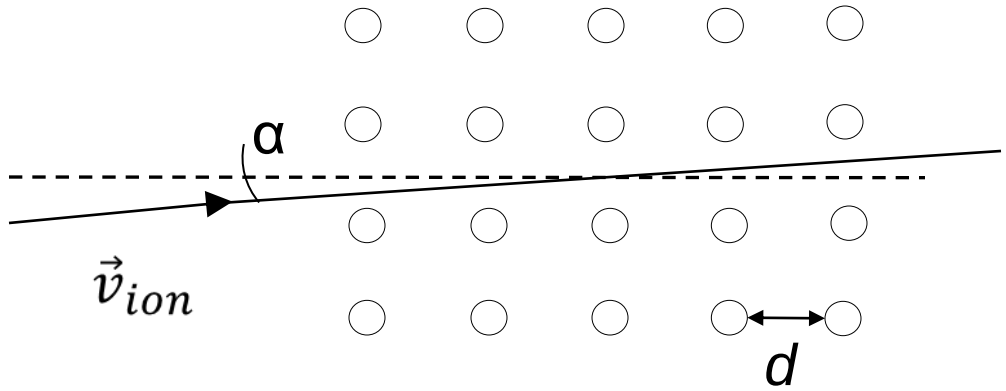


Planar channeling



Non-channeling

Resonant Coherent Excitation



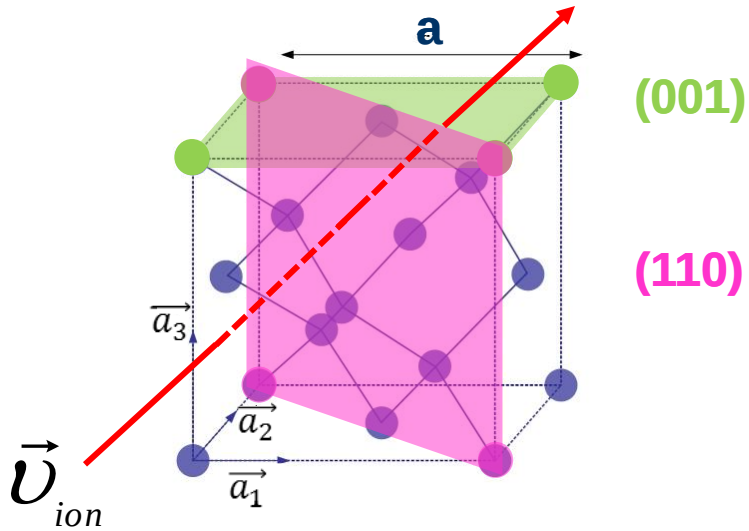
$$\nu_{field} = \gamma\, k\, \frac{\vec{v}_{ion}}{d}, k = 1,2,3, \ldots$$

$$\nu_{\gamma} = \frac{E_{tr}}{h}$$

RCE condition: $\nu_{field} = \nu_{\gamma}$ → **Ion energy & Crystal orientation**

γ – Lorenz factorz

RCE conditions



Si-crystal unit cell: face centered cubic structure.

$$\nu_{field} = \nu_{\gamma}$$

$$h\nu_{\gamma} = E_{tr}$$

Frequency of the field $\nu_{field} = \gamma\,\vec{g}\cdot\vec{\upsilon}_{ion}$ **where** $\vec{g} = k\vec{a}_1^{\,*} + l\vec{a}_2^{\,*} + m\vec{a}_3^{\,*}$

θ **is angle between the beam axis and [1,1,0] axis in the (2,2,0) plane of Si**

$$h\nu_{field} = E_{tr} = \frac{h\gamma\upsilon_{ion}}{a} f_{klm}(\theta,\varphi),$$ **where** $$f_{klm}(\theta,\varphi) = \sqrt{2}(k\cos\varphi + m\sin\varphi)\cos\theta + l\sin\theta$$

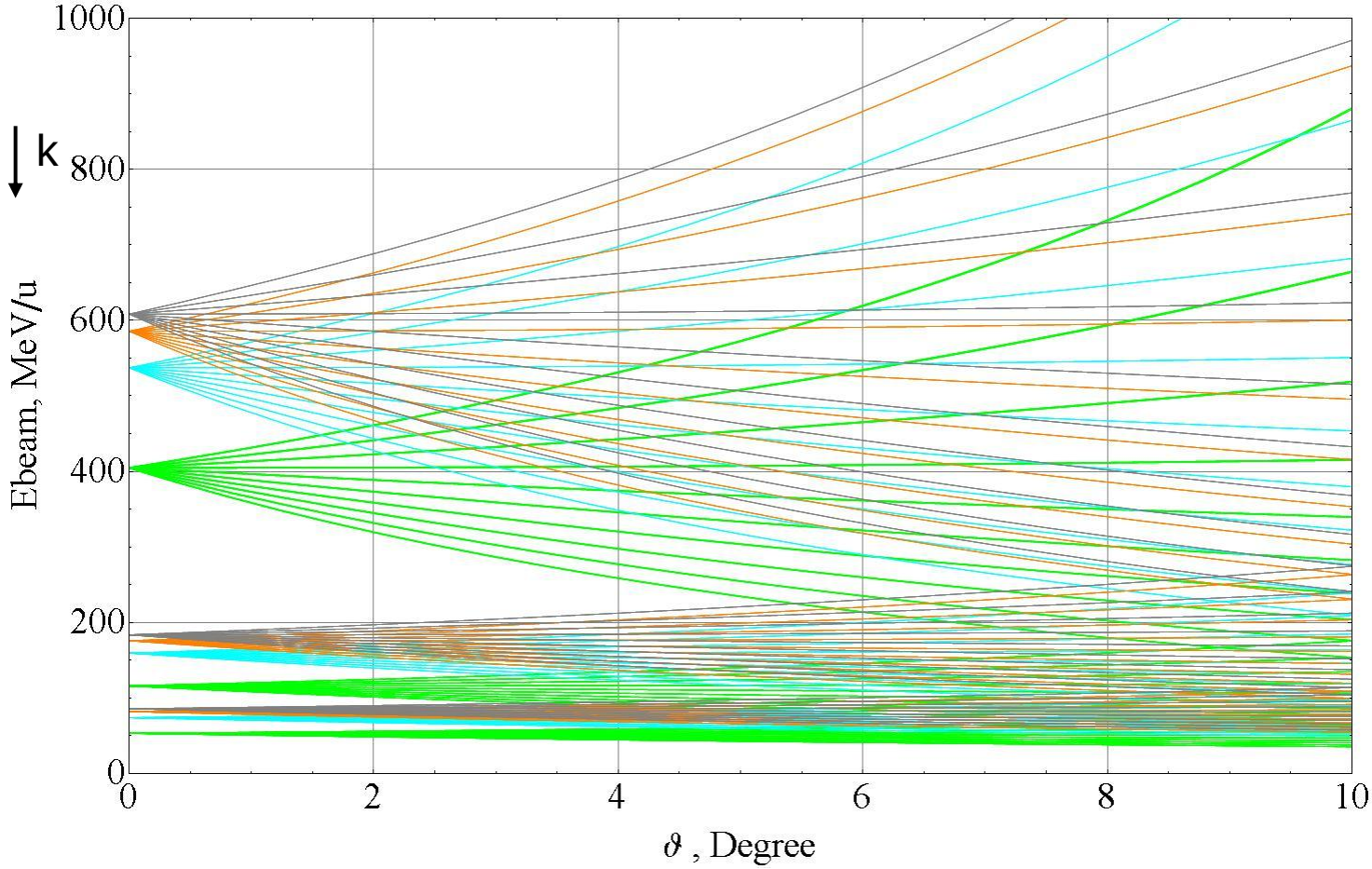
a – lattice constant ; k,l,m – Miller indexes

Resonance condition for H-like Ar

$$E_{tr} = \frac{h\gamma\upsilon}{a}\{\sqrt{2}(k\cos\varphi + m\sin\varphi)\cos\theta + l\sin\theta\}$$

Planar orientation Si (220)

455 MeV/u Ar^{17+}
k=1
$4^\circ < \theta < 6^\circ$
$\varphi = 0^\circ$



[4]

0< k< 3
-5< l < 5
-5 < m < 5

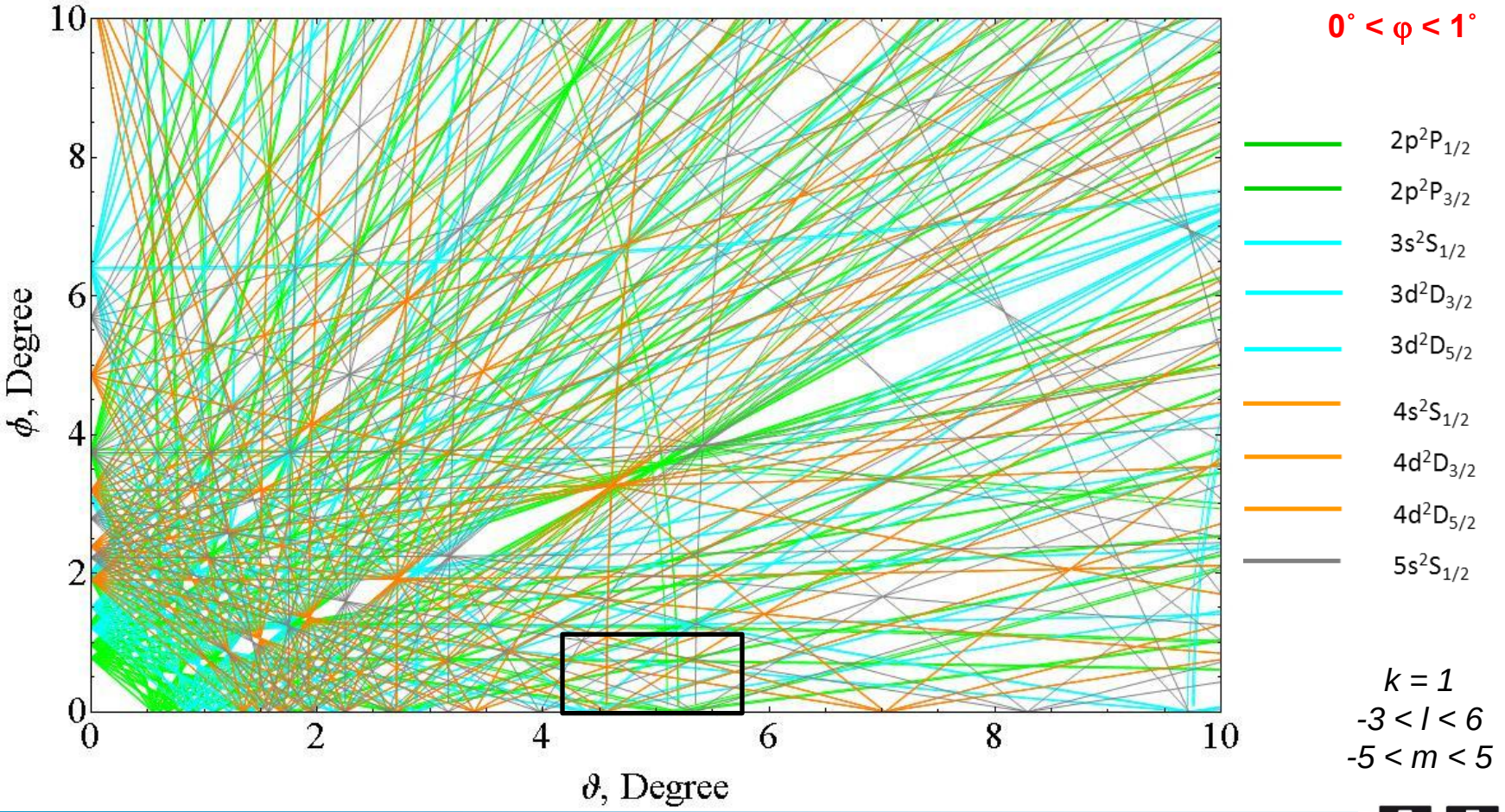
[4] NIST Database

Resonance condition for H-like Ar

$$E_{tr} = \frac{h\gamma\upsilon}{a}\{\sqrt{2}(k\cos\varphi + m\sin\varphi)\cos\theta + l\sin\theta\}$$

non-channeling orientation

455 MeV/u Ar^{17+}
k=1
$4^\circ < \theta < 6^\circ$
$0^\circ < \varphi < 1^\circ$



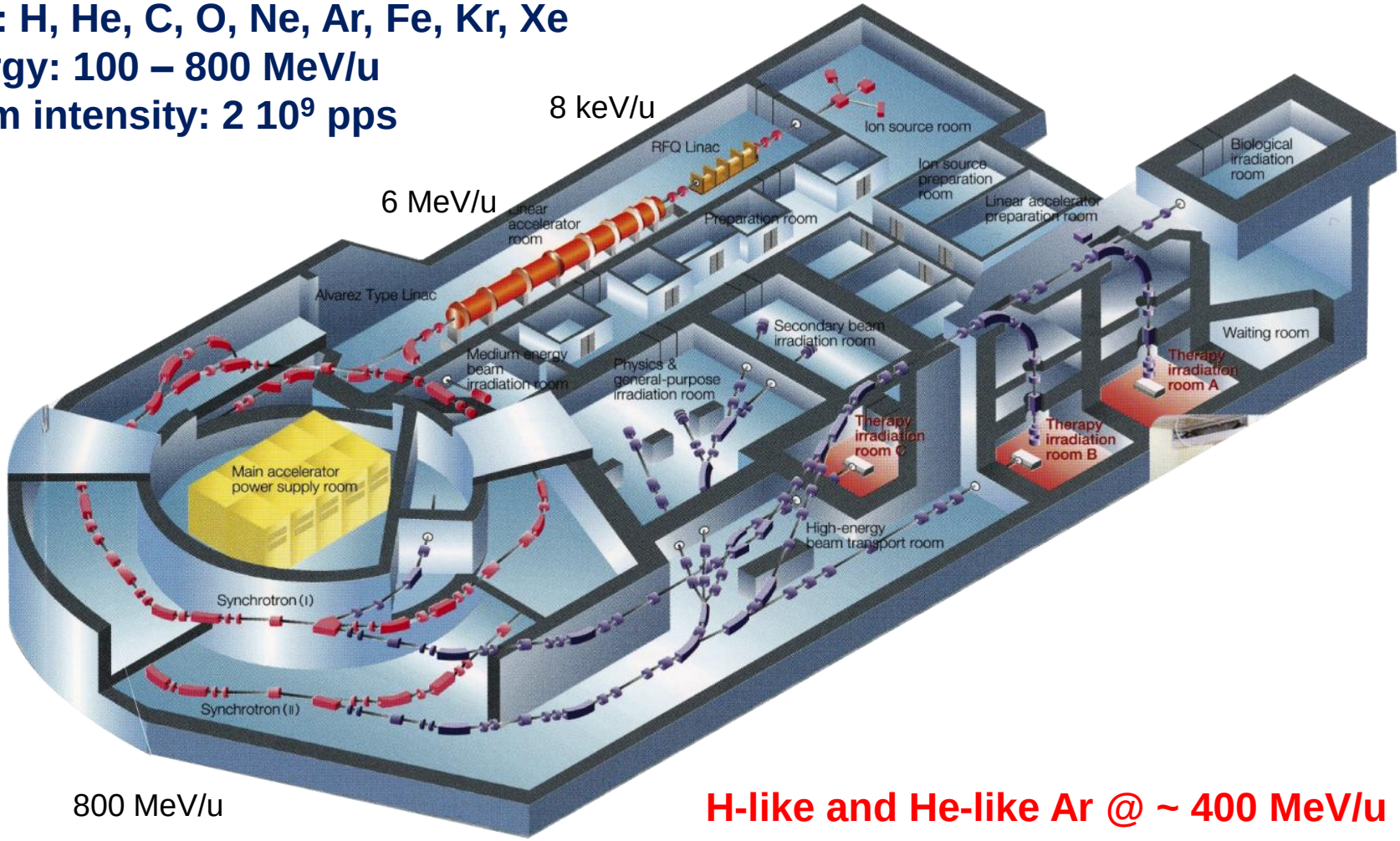
[4]

k = 1
-3 < l < 6
-5 < m < 5

[4] NIST Database

HIMAC facility (Chiba, Japan)

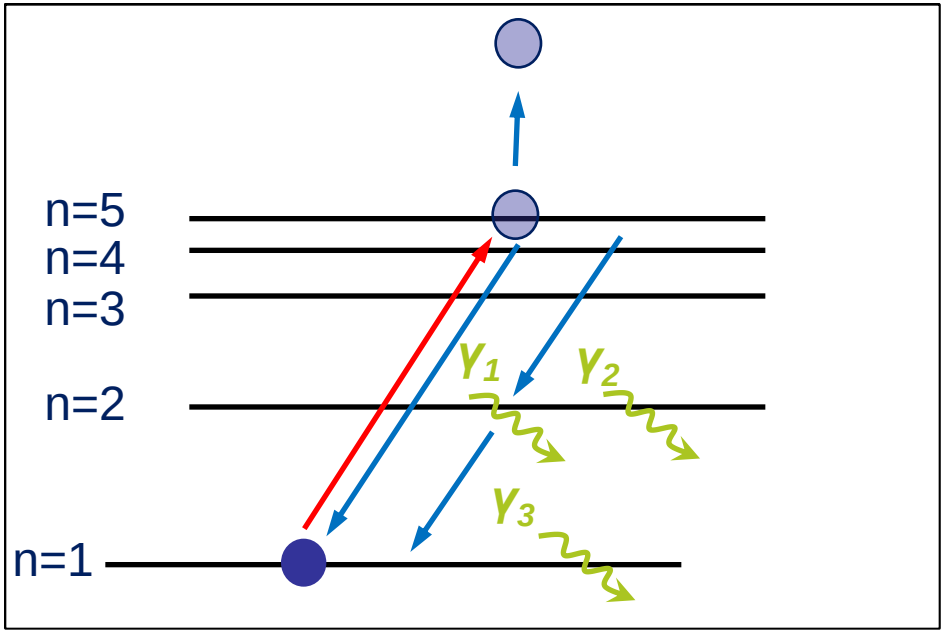
Ions: H, He, C, O, Ne, Ar, Fe, Kr, Xe
Energy: 100 – 800 MeV/u
Beam intensity: 2 10^9 pps



H-like and He-like Ar @ ~ 400 MeV/u

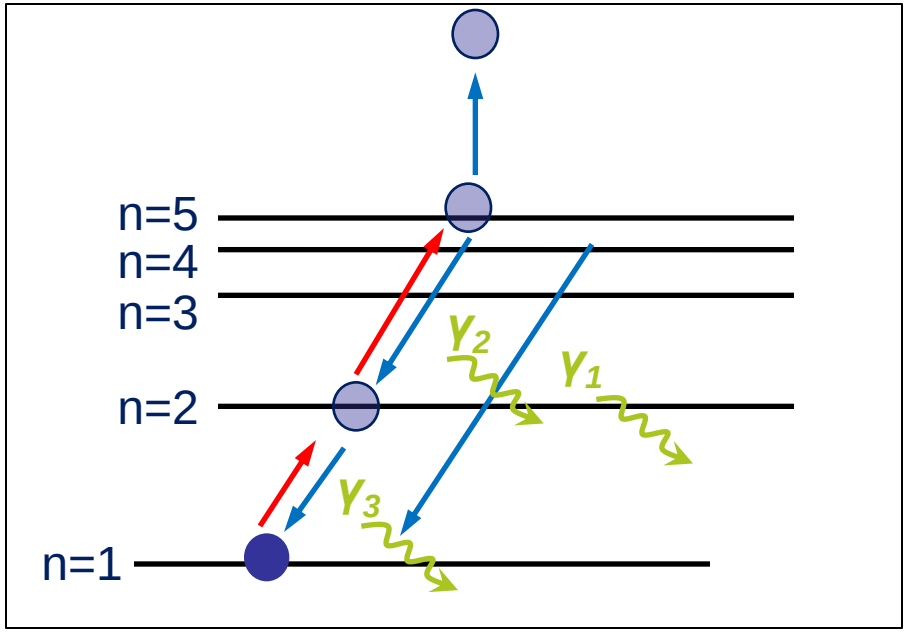
RCE in H-like ions

Single RCE



$\nu_{field1,2}$ or $\nu_{field1,5}$

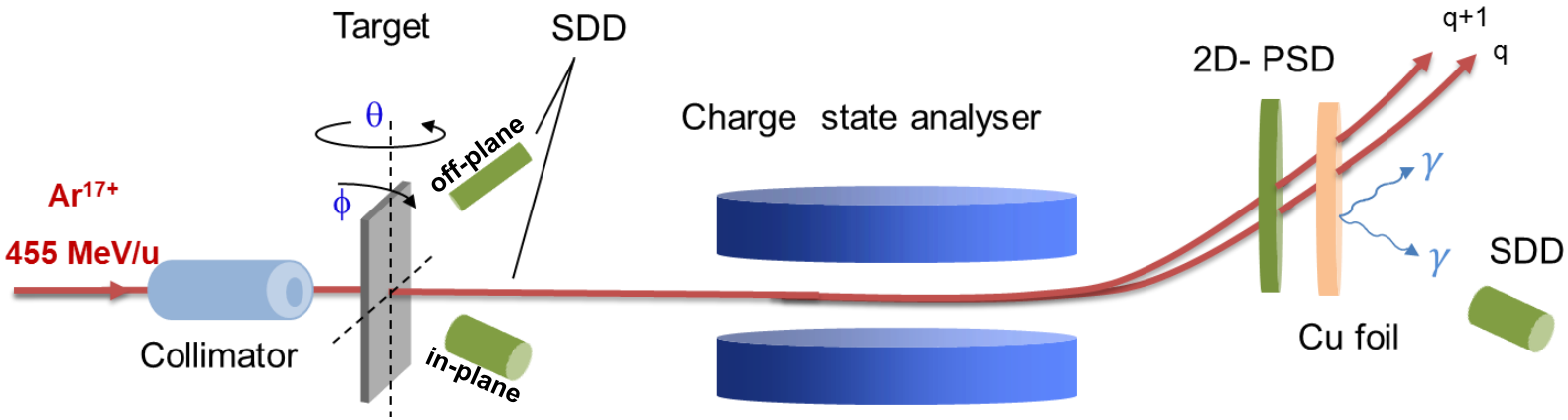
Double RCE

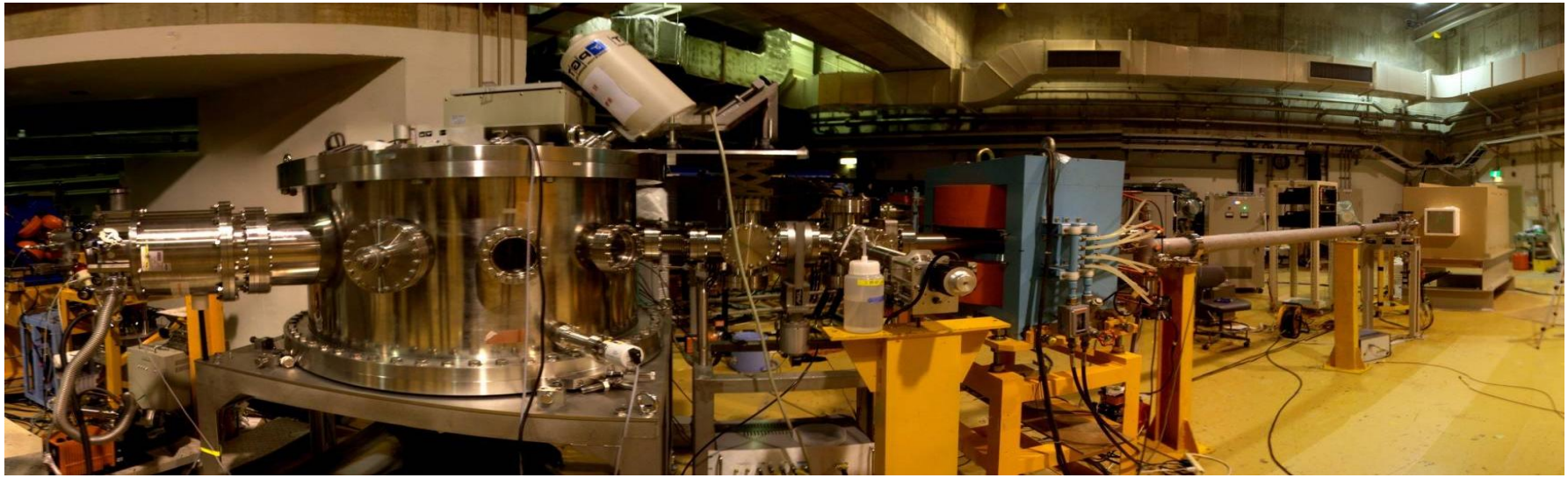


$\nu_{field1,5}$ and $\nu_{field1,2}$

$\nu_{field2,5}$

Setup at HIMAC

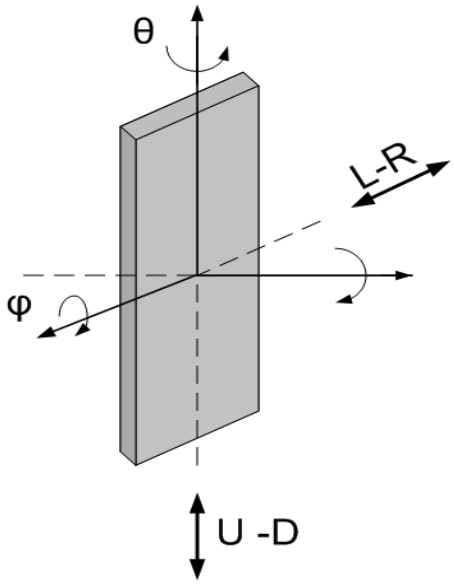


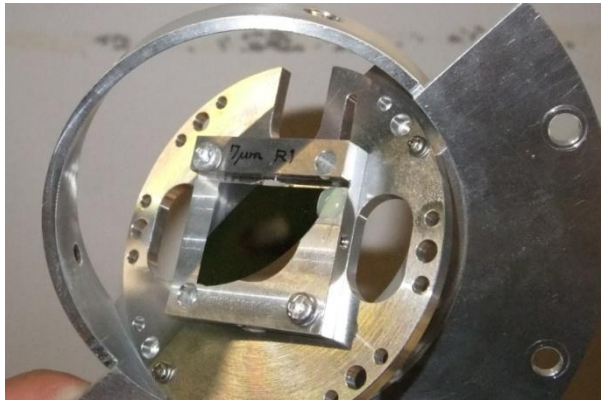


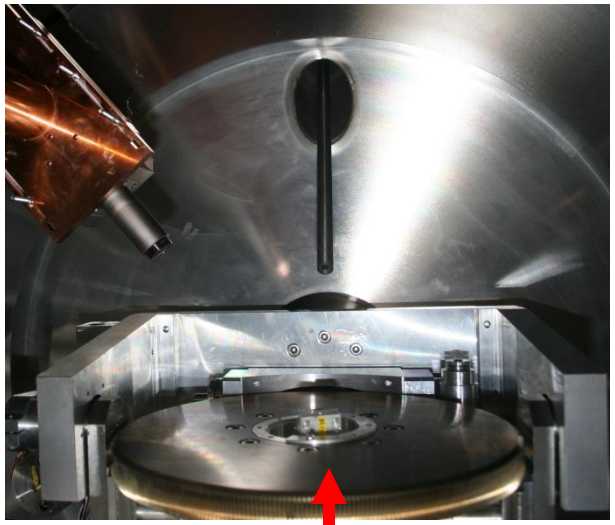
- **Charge-state distribution ions**
- **X-rays from the excited states**

Target and Gonio

Si-crystal: **1 µm thickness**
100 mm² area







ion beam

Target alignment along 2 direction and rotation around 3 axis

Detectors

X-rays detection

Silicon Drift Detectors (SDD) [5]

- 80 mm^2 active area
- 450 µm thickness
- $\varepsilon = \sim 99\%$ for $E\gamma$= 5.9 keV
- Solid angle ~ $4.7*10^{-3}$
- Reset-type low noise preamplifier
- Peltier cooling system (+20°C)
- Vacuum compatible
- Calibration Fe^{55} FWHM = 190 eV @ 5.9 keV

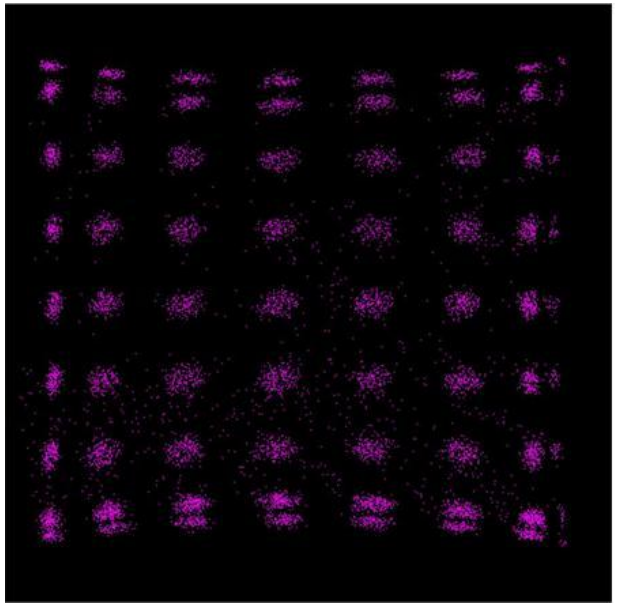
SiLi detector [6]

- 30 mm^2 active area
- 6 mm thickness
- $\varepsilon = \sim 99\%$ for $E\gamma$= 5.9 keV
- Solid angle ~ $2*10^{-3}$
- Liquid N_2 cooling system
- Vacuum compatible
- Calibration Fe^{55} FWHM = 160 eV @ 5.9 keV

Ions detection

2D Si-based PSD

- 400 mm² PSD, 4 sectors
- Read out – charge splitting
- Better than 2 mm position resolution (PCB Mask)
- Rate dependent detection efficiency!



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

RCE in H-like Ar

- ✓ **Beam of H-like Ar @ 390 MeV/u**
- ✓ **1 μm Si-crystal target**
- ✓ **$4^\circ < \theta < 6^\circ$ and $1.5^\circ < \theta < 2^\circ$**
- ✓ **$0^\circ < \varphi < 1^\circ$**
- ✓ **Miller indices:**

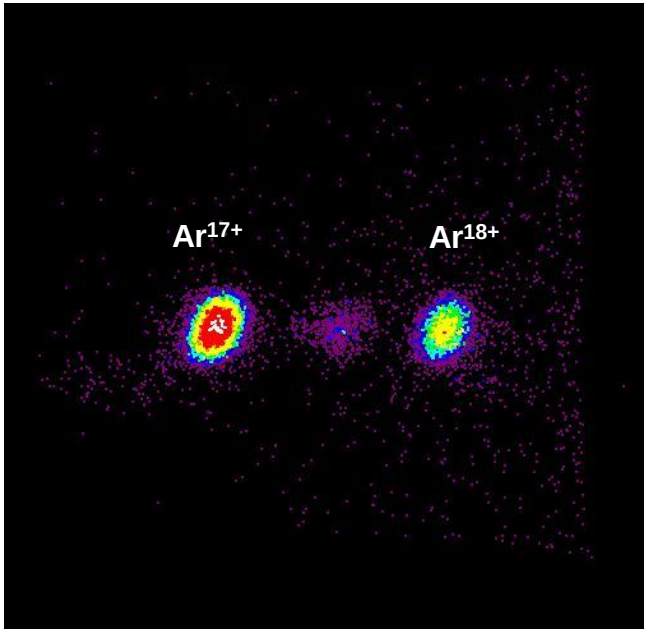
k=1
$-3 < l < 11$
$-5 < m < 5$

Transition	Energy, eV
$2p\ ^2P_{3/2}$	3322.9919
$3s\ ^2S_{1/2}$	3934.34013
$3d\ ^2D_{3/2}$	3935.717996
$3d\ ^2D_{5/2}$	3936.189976

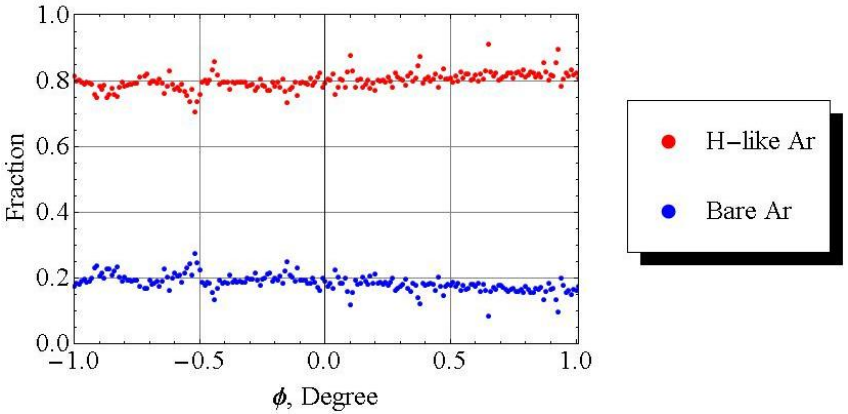
- **Charge states distribution of the ion yield**
- **X-rays from the decay of the excited states**

[4] NIST Database

Charge states distribution of the ion yield

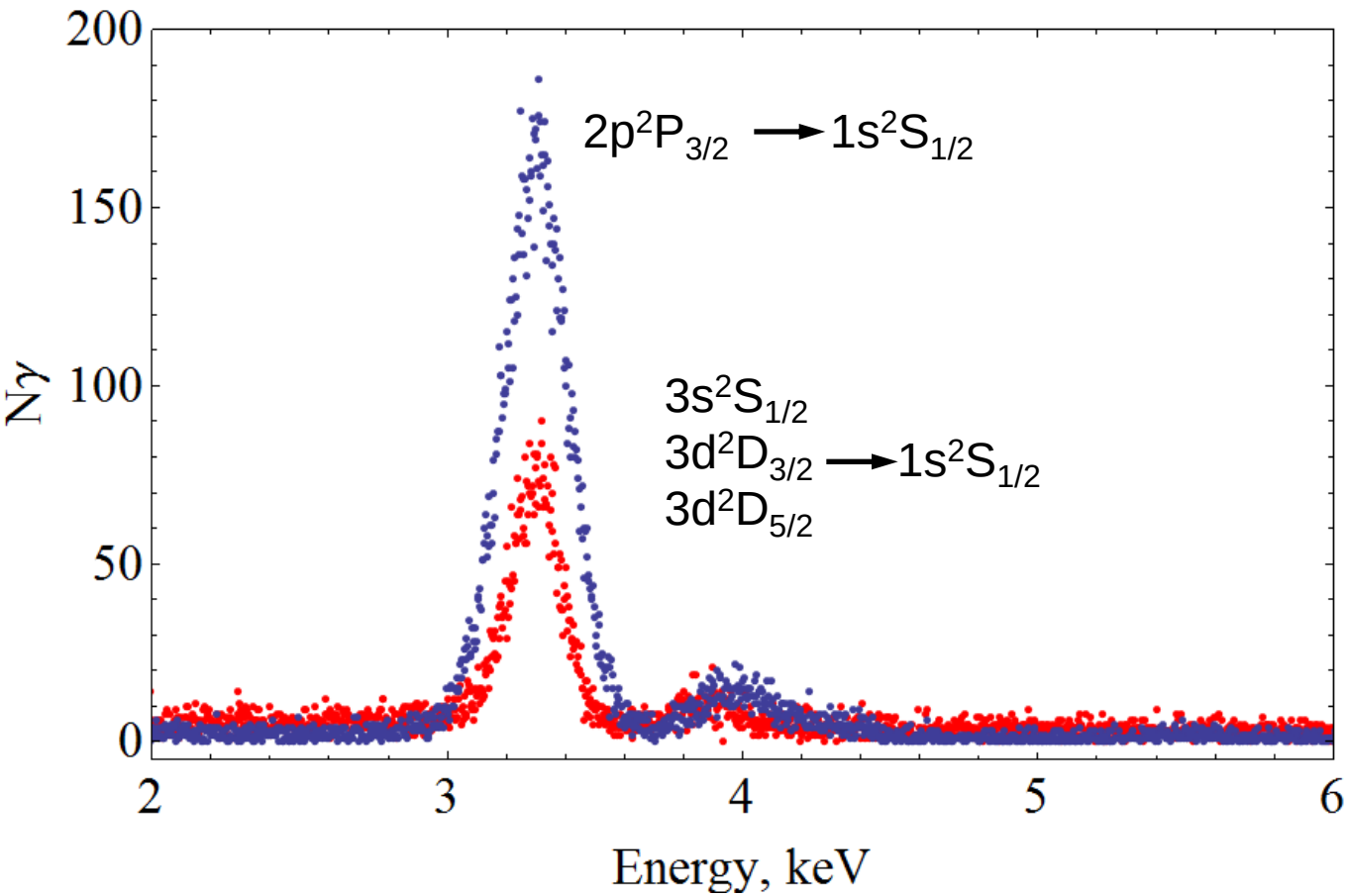


Charge-state distribution of the 390 MeV/u Ar^{17+} ions after passing 1 μm Si-crystal



Charge-state distribution of the 390 MeV/u Ar^{17+} ions after passing 1 μm Si-crystal at the random orientation

X-Rays Measurement



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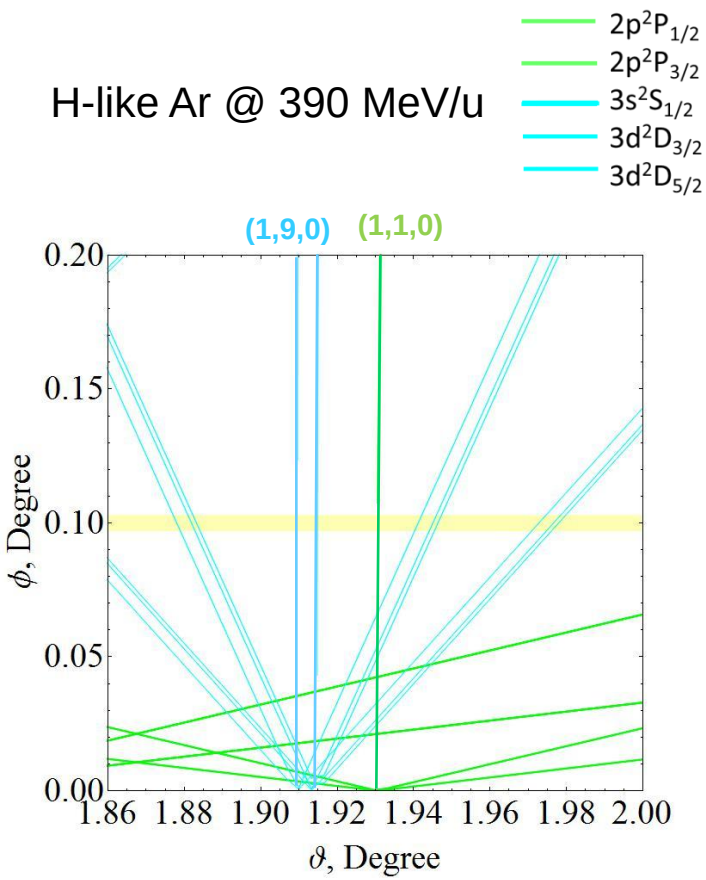
$3d\ ^2D_{5/2}$	3936.189976

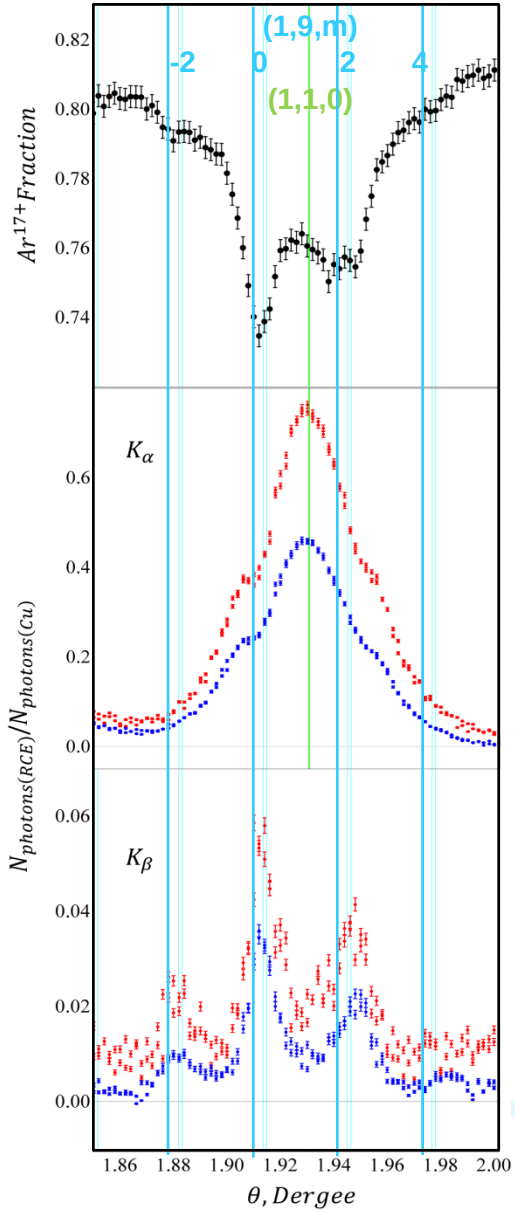
Off-plane
In-plane

The x-ray spectrum from 390 MeV/u Ar^{17+} ions coherently excited in a Si-crystal

Resonance spectra n=2&3

H-like Ar @ 390 MeV/u





off-plane
in-plane

1s → 2p → 3s&d

RCE in He-like Ar

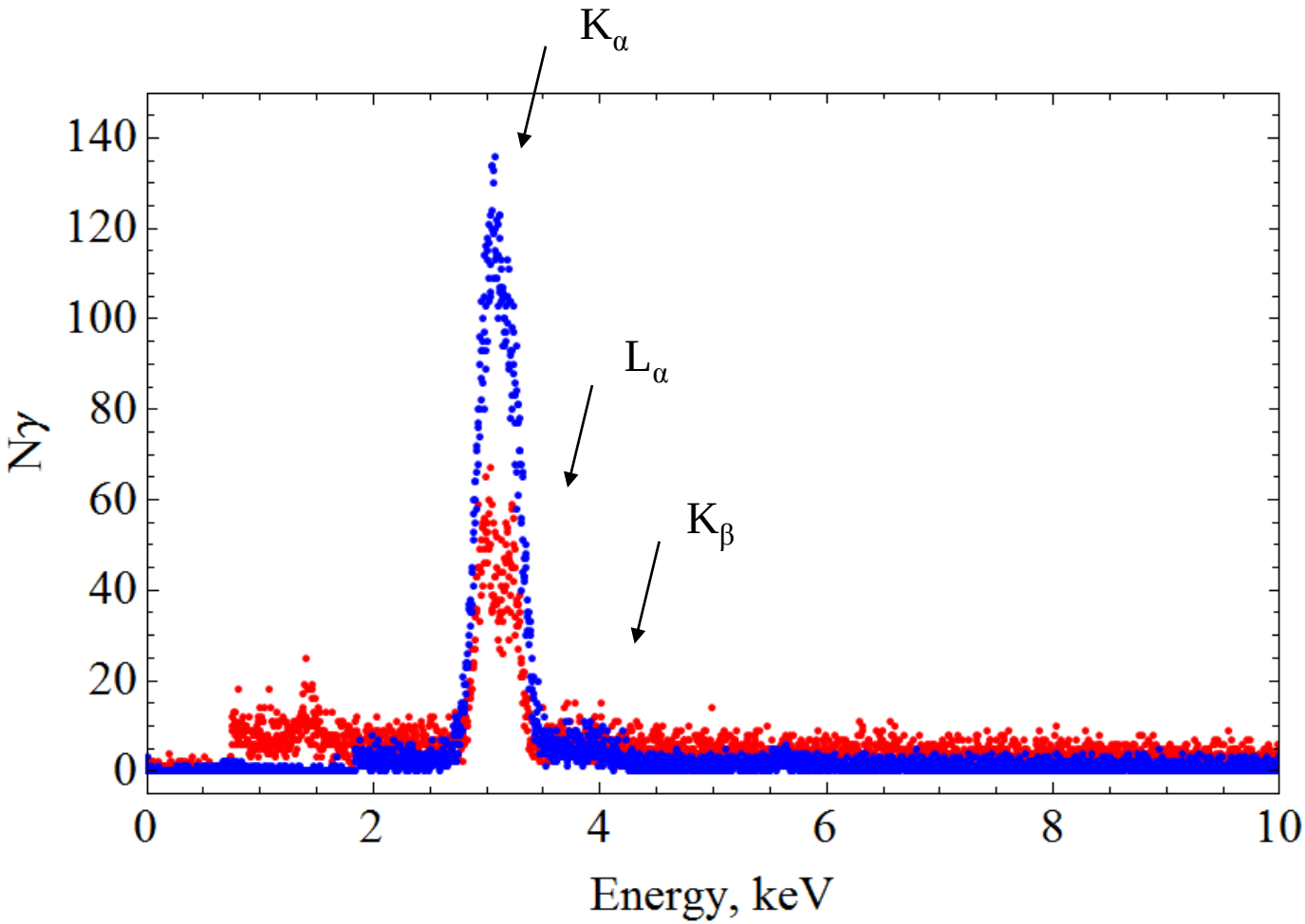
- ✓ Beam of He-like Ar @ 381 MeV/u
- ✓ 1 μm Si-crystal target
- ✓ $1.6^\circ < \theta < 1.75^\circ$
- ✓ $0^\circ < \varphi < 0.3^\circ$
- ✓ Miller indices:

$$k = 0, 1$$
$$-1 < l < 9$$
$$-5 < m < 5$$

Transition	Energy, eV
1s2p $^1P_1$	3139.5823
1s3s $^1S_0$	3679.461
1s3d $^1D_2$	3683.589

- Charge states distribution of the ion yield
- X-rays from the decay of the excited states

X-Rays Measurement He-like Ar

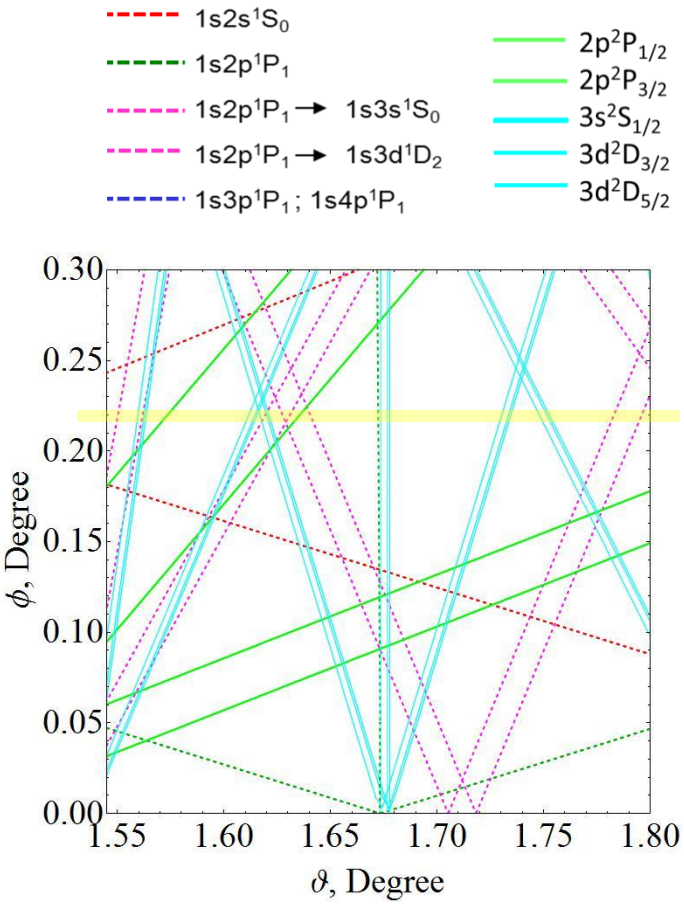


Transition	Energy, eV
1s2p $^1P_1$	3139.5823
1s3s $^1S_0$	3679.461
1s3d $^1D_2$	3683.589

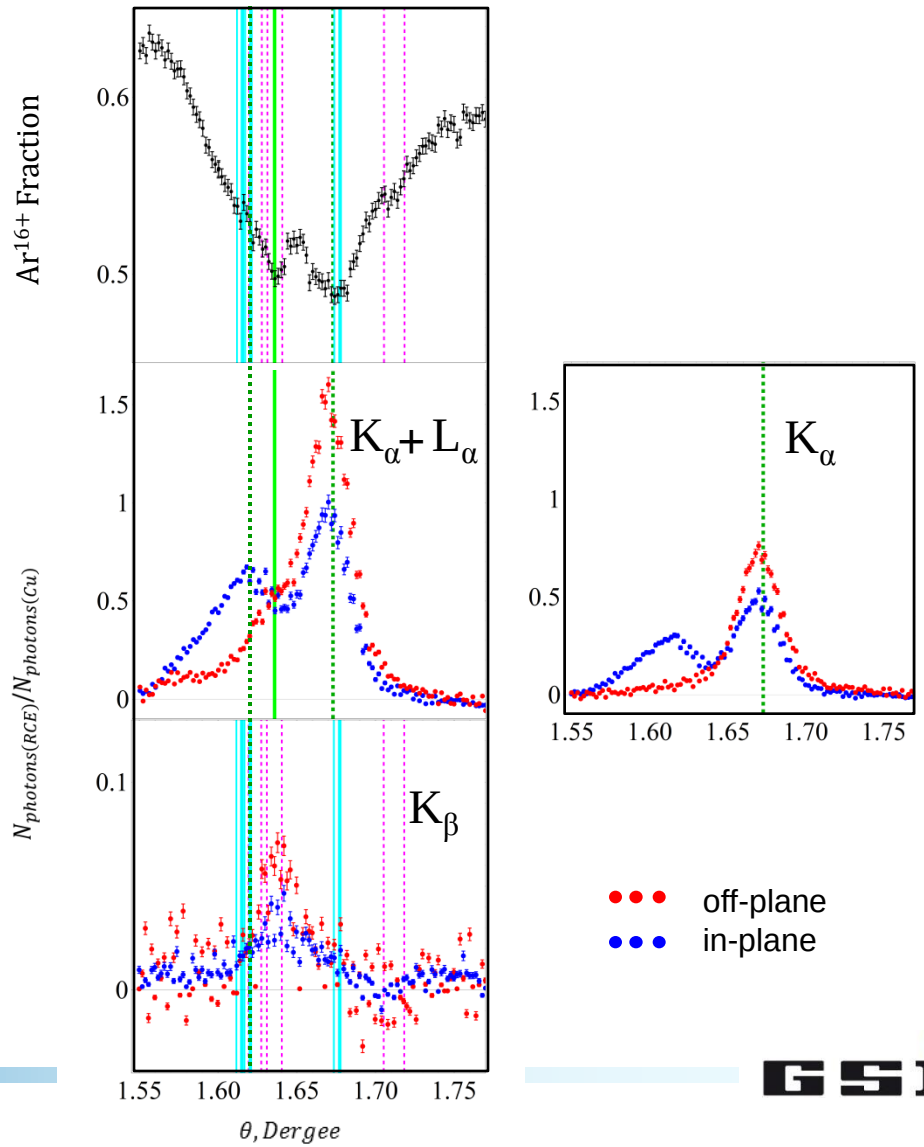
Off-plane
In-plane

The X-ray spectrum from 381MeV/u Ar^{17+} ions coherently excited in a Si-crystal

Resonance spectra from He-like Ar

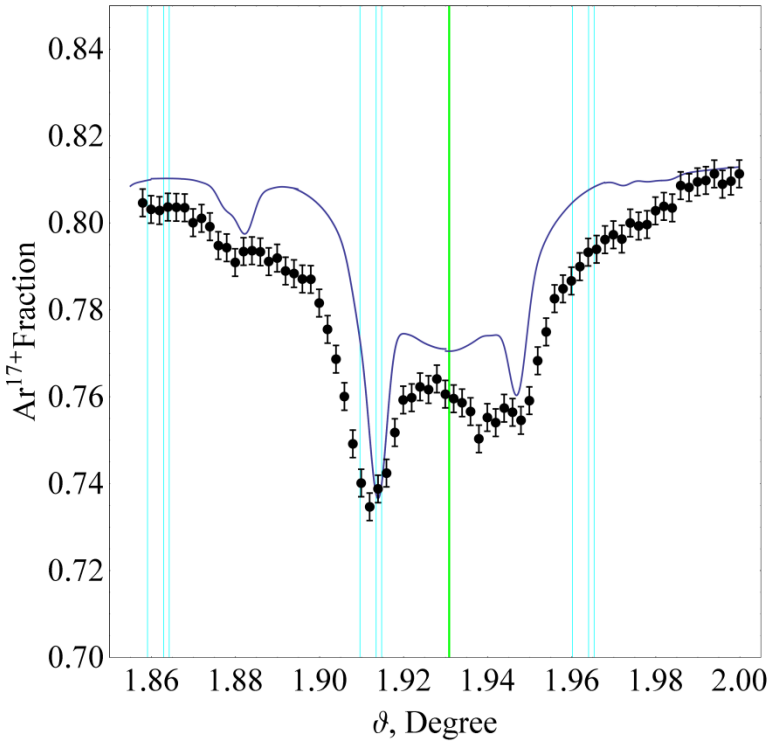


H-like & He-like Ar @ 381MeV/u



Resonance spectra from H-like Ar

H-like Ar @ 390 MeV/u



Moliere approximation of a crystal field [5]:

$$u_0(\mathbf{R}) = \frac{Z_{\mathrm{cr}} q}{R} \sum_{1}^{3} a_j \exp\left(-\frac{b_j R}{a_{\mathrm{TF}}}\right)$$

$2p^2P_{1/2}$
$2p^2P_{3/2}$
$3s^2S_{1/2}$
$3d^2D_{3/2}$
$3d^2D_{5/2}$

Theory [A.Babaev]

Experiment

Survival fraction of the initial charge-state

[5] D. S. Gemmel, Rev.Mod.Phys. **46**, 129 (1974)

Summary and Outlook

- Double RCE of H-like and He-like Ar was observed by the measurement of the charge-state distribution of the ions and the x-ray yield. Double RCE was detected as two step excitation, from the n=1 to n=2 and further to higher *n* states
- The measurements were made out-of channeling conditions
- RCE in Li-like Ar
- Observation of the electron emission: energy dependent, poor statistics

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- Theoretical model of the Double RCE → Dr. A. Babaev, Dr. A. Surzhykov
- RCE in many-electron systems
- Coincident detection of photons, electron and/or ions
- Anisotropy measurement → Design of the rotatable system for the x-ray detectors
- RCE in highly-charged U at GSI and FAIR accelerator facility

Thank you!