Observation of Double Resonant Coherent Excitation of Highly-Charged Ions in Crystals
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A. Ananyeva\textsuperscript{a,b}, Y. Nakano\textsuperscript{c,d}, H. Braeuning\textsuperscript{b}, A. Braeuning-Demian\textsuperscript{b}, Y. Kanai\textsuperscript{d}, T. Shindo\textsuperscript{c}, S. Suda\textsuperscript{c}, T. Azuma\textsuperscript{c,d}, Y. Yamazaki\textsuperscript{d}

\textsuperscript{a}Goethe-Universität, Frankfurt am Main, Germany
\textsuperscript{b}GSI Helmholtzzentrum, Darmstadt, Germany
\textsuperscript{c}Tokyo Metropolitan University, Tokyo, Japan
\textsuperscript{d}RIKEN Advanced Science Institute, Tokyo, Japan

Supported by:

GSI - Helmholtzzentrum für Schwerionenforschung GmbH
Grants-in-Aid for Scientific Research (No. 19104010) from JSPS, Japan.
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) : $E_{\text{beam}} = 100 - 800$ MeV/u (HIMAC)
➢ Atomic RCE in U (intra-shell, < 10 keV) : $E_{\text{beam}} = 100 - 400$ MeV/u (GSI)

Future:
➢ Atomic and Nuclear RCE (~ 100 keV) : $E_{\text{beam}} < 10$ GeV/u (FAIR)

Motivation

1s-2p transition

2s-2p transition

Z=92
Motivation

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

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

$\langle E \rangle$ [V/cm]

Nuclear Charge, $Z$

Hydrogen

Uranium

Ar

Laser field
Ion-atom interaction

Ion + atom

- Electron capture
- Ionization
- Excitation

Excitation → De-excitation

Ionization

Photoemission
Ion motion in a crystal

Crystal field:

\[ \vec{\phi}(r) = \sum_n \phi_n \exp(2\pi i g \cdot \vec{r}) \]
Resonant Coherent Excitation

RCE condition: \( v_{field} = v_{\gamma} \)  \quad \text{Ion energy & Crystal orientation}

\( v_{field} = \gamma k \frac{\mathbf{v}_{ion}}{d} , k = 1,2,3, ... \)

\( v_{\gamma} = \frac{E_{tr}}{\hbar} \)

\( \gamma \) – Lorenz factor
RCE conditions

Si-crystal unit cell: face centered cubic structure.

\[ \nu_{field} = \nu_\gamma \]

\[ h \nu_\gamma = E_{tr} \]

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

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

\[ h \nu_{field} = E_{tr} = \frac{h \nu_{ion}}{a} f_{klm}(\theta, \varphi), \quad \text{where} \quad f_{klm}(\theta, \varphi) = \sqrt{2}(k \cos \varphi + m \sin \varphi) \cos \theta + l \sin \theta \]

\( a \) – lattice constant ; \( k,l,m \) – Miller indexes
Resonance condition for H-like Ar

\[ E_{tr} = \frac{\hbar \nu}{a} \sqrt{2} (k \cos \varphi + m \sin \varphi) \cos \theta + l \sin \theta \]

Planar orientation Si (220)

455 MeV/u Ar\(^{17+}\)

\[ k=1 \]

\[ 4^\circ < \theta < 6^\circ \]

\[ \varphi = 0^\circ \]

[4] NIST Database

0 < k < 3

-5 < l < 5

-5 < m < 5
Resonance condition for H-like Ar

\[ E_{tr} = \frac{h\nu}{a} \{ \sqrt{2} (k \cos \varphi + m \sin \varphi) \cos \theta + l \sin \theta \} \]

non-channeling orientation

455 MeV/u Ar\textsuperscript{17+}

\[ k = 1 \]

\[ 4^\circ < \theta < 6^\circ \]

\[ 0^\circ < \varphi < 1^\circ \]

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: $2 \times 10^9$ pps

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

Single RCE

\[ n=1 \quad \rightarrow \quad n=2 \quad \rightarrow \quad n=3 \quad \rightarrow \quad n=4 \quad \rightarrow \quad n=5 \]

\[ \gamma_1, \gamma_2, \gamma_3 \]

\[ V_{field\,1,2} \quad \text{or} \quad V_{field\,1,5} \]

Double RCE

\[ n=1 \quad \rightarrow \quad n=2 \quad \rightarrow \quad n=3 \quad \rightarrow \quad n=4 \quad \rightarrow \quad n=5 \]

\[ \gamma_1, \gamma_2, \gamma_3 \]

\[ V_{field\,1,5} \quad \text{and} \quad V_{field\,1,2} \quad \text{and} \quad V_{field\,2,5} \]
Setup at HIMAC

- Charge-state distribution ions
- X-rays from the excited states
**Si-crystal:** 1 μm thickness  
100 mm² area

Target alignment along 2 direction  
and rotation around 3 axis

**Target and Gonio**
Detectors

X-rays detection

Silicon Drift Detectors (SDD) [5]
- 80 mm² active area
- 450 μm thickness
- \( \varepsilon = \sim 99\% \) for \( E_\gamma = 5.9 \) keV
- Solid angle \( \sim 4.7 \times 10^{-3} \)
- 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 mm² active area
- 6 mm thickness
- \( \varepsilon = \sim 99\% \) for \( E_\gamma = 5.9 \) keV
- Solid angle \( \sim 2 \times 10^{-3} \)
- 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!

RCE in H-like Ar

- Beam of H-like Ar @ 390 MeV/u
- 1 μm Si-crystal target
- 4° < θ < 6° and 1.5° < θ < 2°
- 0° < φ < 1°
- Miller indices:
  - k=1
  - -3 < l < 11
  - -5 < m < 5

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<th>Transition</th>
<th>Energy, eV</th>
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<td>2p 2P_{3/2}</td>
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<td>3d 2D_{5/2}</td>
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- Charge states distribution of the ion yield
- X-rays from the decay of the excited states
Charge states distribution of the ion yield

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

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

$1s \rightarrow 2p \rightarrow 3s$&$d$

A. Ananyeva
✓ Beam of He-like Ar @ 381 MeV/u
✓ 1 μm Si-crystal target
✓ 1.6° < θ < 1.75°
✓ 0° < φ < 0.3°
✓ Miller indices:

\[ k = 0, 1 \]
\[ -1 < l < 9 \]
\[ -5 < m < 5 \]

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<td>1s2p (^1P_1)</td>
<td>3139.5823</td>
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<tr>
<td>1s3s (^1S_0)</td>
<td>3679.461</td>
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<td>1s3d (^1D_2)</td>
<td>3683.589</td>
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- Charge states distribution of the ion yield
- X-rays from the decay of the excited states
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

Moliere approximation of a crystal field [5]:

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

\( Z_{cr} \) is the average number of atomic charges in the crystal field of the target, \( q \) is the charge of the incoming projectile, \( a_j \) are the wavefunction overlap integrals, and \( b_j \) and \( a_{TF} \) are parameters of the Moliere potential.

Survival fraction of the initial charge-state
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

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!