High-Resolution Microcalorimeter Measurement of X-Ray Transitions in He-like Uranium at CRYRING@ESR

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He-Like Atomic/Ionic Systems

\[\begin{align*}
[1s_{1/2}, 2s_{1/2}] & \quad ^3S_0 \\
[1s_{1/2}, 2s_{1/2}] & \quad ^3S_1 \\
[1s_{1/2}, 1s_{1/2}] & \quad ^1S_0 \\
\end{align*}\]

E1 (Kα₁)
M2 (Kα₂)
M1 (Kα₁)
E1 (Kα₂)

\[\begin{align*}
[1s_{1/2}, 2p_{3/2}] & \quad ^3P_1 \\
[1s_{1/2}, 2p_{3/2}] & \quad ^3P_2 \\
[1s_{1/2}, 2p_{1/2}] & \quad ^3P_0 \\
[1s_{1/2}, 2p_{1/2}] & \quad ^3P_1 \\
\end{align*}\]

\(E = 1.8 \times 10^{16} \text{ V/cm}\)
\(E_b = -132 \text{ keV}\)

\(E = 1 \times 10^{10} \text{ V/cm}\)
\(E_b = -13.6 \text{ eV}\)
Evidence for a Z-dependent Divergence Between Experiment and Calculation
(C. T. Chantler et al., PRL 109, 153001 (2012))
GSI / FAIR: Acceleration & Deceleration of Ions

**Ion source U⁷⁺**
- **U²⁸⁺ 1.4 MeV/u**
- **UNILAC - Accel**
- **U⁷³⁺ 11.4 MeV/u**
- **SIS 18 - Accel**
- **U⁹¹⁺ 400 MeV/u**
- **ESR - Decel**
- **U⁹¹⁺ 10 MeV/u**
- **CRYRING@ESR**
  - **U⁹¹⁺ 10 MeV/u**
Spectroscopy of U\(^{90+}\) at CRYRING@ESR Electron Cooler

- Adapting the well-proven, successful concept from the ESR cooler to CRYRING@ESR, applying novel high resolution calorimeter detectors.

- CRYRING@ESR: Factor 4 enhanced luminosity compared to ESR

**Metallic magnetic microcalorimeter**

Working principle

- $\varepsilon = 10^{-7}$

- Microcalorimeter arrays for high-resolution X-ray spectroscopy (maXs)

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The New Experimental Setup at CRYRING@ESR

**Key features:**

0° and 180° observation angles
⇒ Insensitivity to geometrical misalignment

**Beryllium windows ①**
⇒ High transmission also in the low photon-energy range

**Energy calibration ②**
⇒ Control of detector response function

**High-resolution microcalorimeter detectors ③**
⇒ Improved line centroid determination
Advantages of the Measurement Positions at CRYRING Electron Cooler

Uncertainties due to relativistic Doppler shift are greatly reduced at a low beam energy and with two detectors at 0° and 180°.

\[ E_{\text{lab}}(0°) + E_{\text{lab}}(180°) = \frac{2 \cdot E_{\text{proj}}}{\gamma} \]

- \( E_{\text{lab}} \): Photon energy in the laboratory system
- \( E_{\text{proj}} \): Photon energy in the emitter system

Example:
- 358 MeV/u (\( \beta = 0.69 \))
- 220 MeV/u (\( \beta = 0.59 \))
- 68 MeV/u (\( \beta = 0.36 \))
- 5 MeV/u (\( \beta = 0.10 \))
What are Microcalorimeters?

»Very small thermometer for measuring single particle energies«

Particle with energy $\Delta E$

Change in temperature $\Delta T$

Signal $\Delta U$

Absorber → Sensor → Thermal link

Thermal bath @ 10 mK

maXs-30
### Detector parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area:</td>
<td>$1 \text{ cm}^2$ (64 pixels, with $1.25 \times 1.25 \text{ mm}^2$ each)</td>
</tr>
<tr>
<td>FWHM at 60 keV:</td>
<td>60 eV</td>
</tr>
<tr>
<td>Efficiency (QE) at 100 keV:</td>
<td>$&gt; 50%$</td>
</tr>
</tbody>
</table>

The microcalorimeter arrays developed within the maXs project are designed for high-resolution X-ray spectroscopy, featuring a compact and highly efficient detector configuration.

![Image of maXs-100 detector](image-url)
Microcalorimeter Arrays for High-resolution X-ray Spectroscopy - maXs

Detector parameters:

Active area: 1 cm² (64 pixels, with 1.25 x 1.25 mm² each)

FWHM at 60 keV: 60 eV

Efficiency (QE) at 100 keV: > 50%

A. Gumberidze et al., PRL 032712 (2004)
maXs-100 Detector - Optimized for 100 keV

Bluefors-cryostat & maXs-detector for 180°

New detector arm and chip developed at Heidelberg University.
Calibration Source Holder/Manipulator

- **Purpose:**
  - mounting and movement of calibration sources
  - shielding the detector from their radiation when parked

- **Features:**
  - controlled motion synchronised with machine status
  - readout of position → source fed into DAQ
  - lead and copper shielding
Beryllium Window Chambers

- **Purpose:** window exchange without breaking CRYRING@ESR vacuum.
- **Features:** self-contained with own vacuum pumps, vacuum sensor and heating jackets.

**Were mounted in January/February 2020 as part of the E138 experiment.**

⇒ Will stay available for future spectroscopy experiments at the CRYRING@ESR electron cooler.
Setup at CRYRING@ESR: Cleaner Spectra + Low Energy Lines

Commissioning CRYRING@ESR (2020)

\[ \text{Pb}^{82+} + e^{-} \rightarrow \text{Pb}^{81+} + \hbar \omega \]

X-rays recorded in coincidence with \( \text{Pb}^{81+} \)

ESR (2005)

\[ \text{U}^{92+} + e^{-} \rightarrow \text{U}^{91+} + \hbar \omega \]

X-rays recorded in coincidence with \( \text{U}^{91+} \)

Low energy transitions, that are virtually unaffected by Lamb shift corrections, will be used for a spectroscopic determination of the Doppler shift.
Experimental Run April 2021

What has been achieved?

✓ Uninterrupted operation over several weeks of the novel maXs detectors

✓ No effect of the EM enviroment of CRYRING@ESR on the detector performance

✓ Positioning of calibration sources in synchronization with the measurement cycle (quasi-continuous calibration)

✓ First demonstration and utilization of the time resolution of the maXs detectors

Thank you to the team
Background Suppression via Coincidences with U^{90+} Ions

We utilized for the first time the time resolution of the maXs detector to suppress the radiation background via a coincidence condition on the detection of down-charged ions.

**Coincidence Peak**

\[ \Delta t \approx 1 \mu s \text{ FWHM} \]
Coincidence Conditions Yield Clear U$^{90+}$ Spectra

Radiative Recombination (RR) into U$^{91+}$

Balmer transitions in U$^{90+}$

Kα in U$^{90+}$

K-RR

Balmer transitions in U$^{90+}$
A Shoutout to the E138 Collaboration

The Ground-State Lamb Shift in the Heaviest Hydrogen-like Ion (U^{23+}): High Resolution X-ray Spectroscopy at the CRYRING Electron Cooler


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42 shifts (=14 days) of beam time at CRYRING@ESR granted.

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Thank you for your attention

Time for questions