Microcalorimeters for Spectroscopy of Highly-Charged Ions

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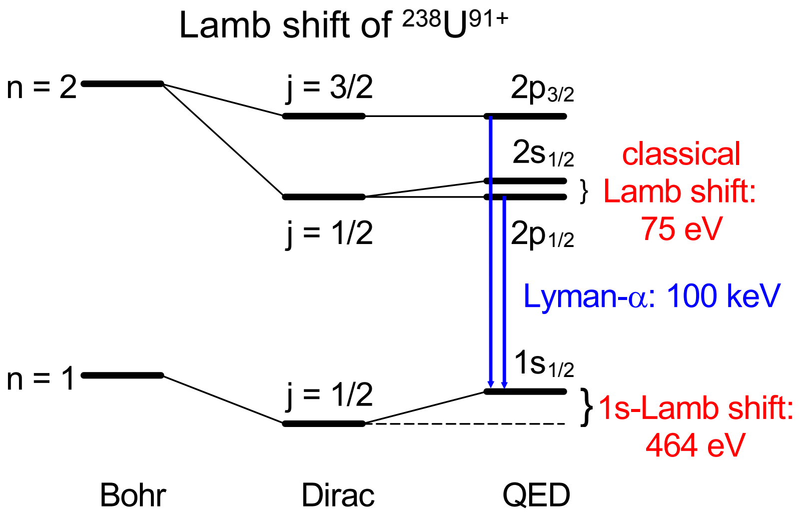
I. Motivation
Precision X-ray Spectroscopy

Example: Determination of the 1s Lamb shift in hydrogen-like heavy ions

- physics interest: precise test of QED
  - ➢ for H-atom: measured with high precision (10^{-6}-level)
    - ➔ excellent agreement with prediction
  - ➢ for high Z: strong Coulomb fields
    - ➔ $Z\alpha \approx 1$: sensitive test still missing

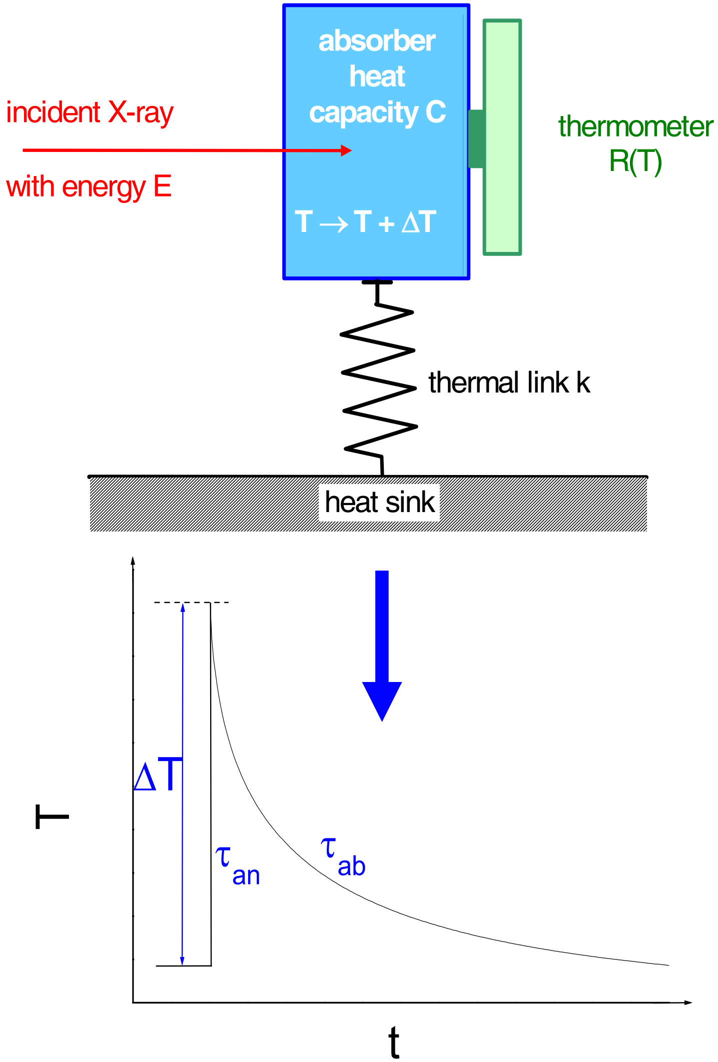


- idea of the experiment:
  measure transition energy of the Lyman-α line for hydrogen-like Pb, U
  $\Rightarrow$ energy resolution determines precision

- theoretical prediction for $^{238}U^{91+}$:
  464.3 ± 0.5 eV (Yerochin et al., Phys.Rev.Lett **91** (2003) 073001)

- experimental value for $^{238}U^{91+}$ (measured at GSI with conventional Ge detectors):
  460.2 ± 4.6 eV (Gumberidze et al., Phys. Rev. Lett. **94** (2005) 223001)
  - ➢ to improve experimental accuracy: microcalorimeters

II. Microcalorimeters



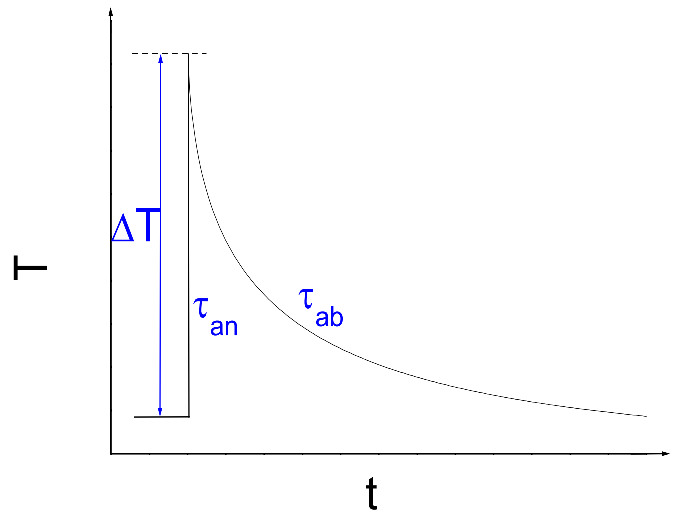
- rise time determined by electronics
- signal height $\Delta T = {}^{E}/_{C}$
- decay time: $t = {}^{C}/_{k}$: 500 µs – 5 ms

- potential advantage:
  - excitation energy of one phonon ~ 1 meV
  - better statistics of detected quanta
  - better energy resolution

Optimization of Detector Parameters

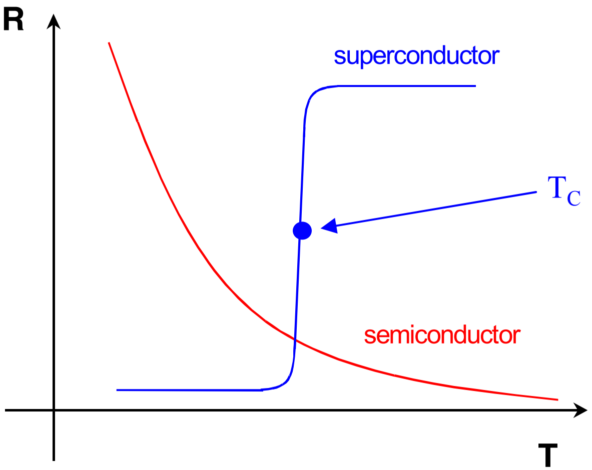
Absorber material:

- Temperature signal $\Delta T = {}^{E}/_{C}$: small heat capacity $C = c \cdot m$
- Debye law for insulators: $c \sim ({}^{T}/_{\Theta_D})^3$
- for superconductors: $c \sim \exp(T/T_C)$
  - ➢ low temperatures
  - ➢ high Debye temperature
- Otherwise, absorber can be adapted to experimental requirements.



Thermometer:

- Resistance thermometer: $\Delta T \rightarrow \Delta R \rightarrow \Delta U$
- for high sensitivity: high dR/dT
- specially doped semiconductor (large dynamic range) or superconductor in phase transition (very high dR/dT)



III. Microcalorimeters for X-rays

Energies 10 – 100 keV:

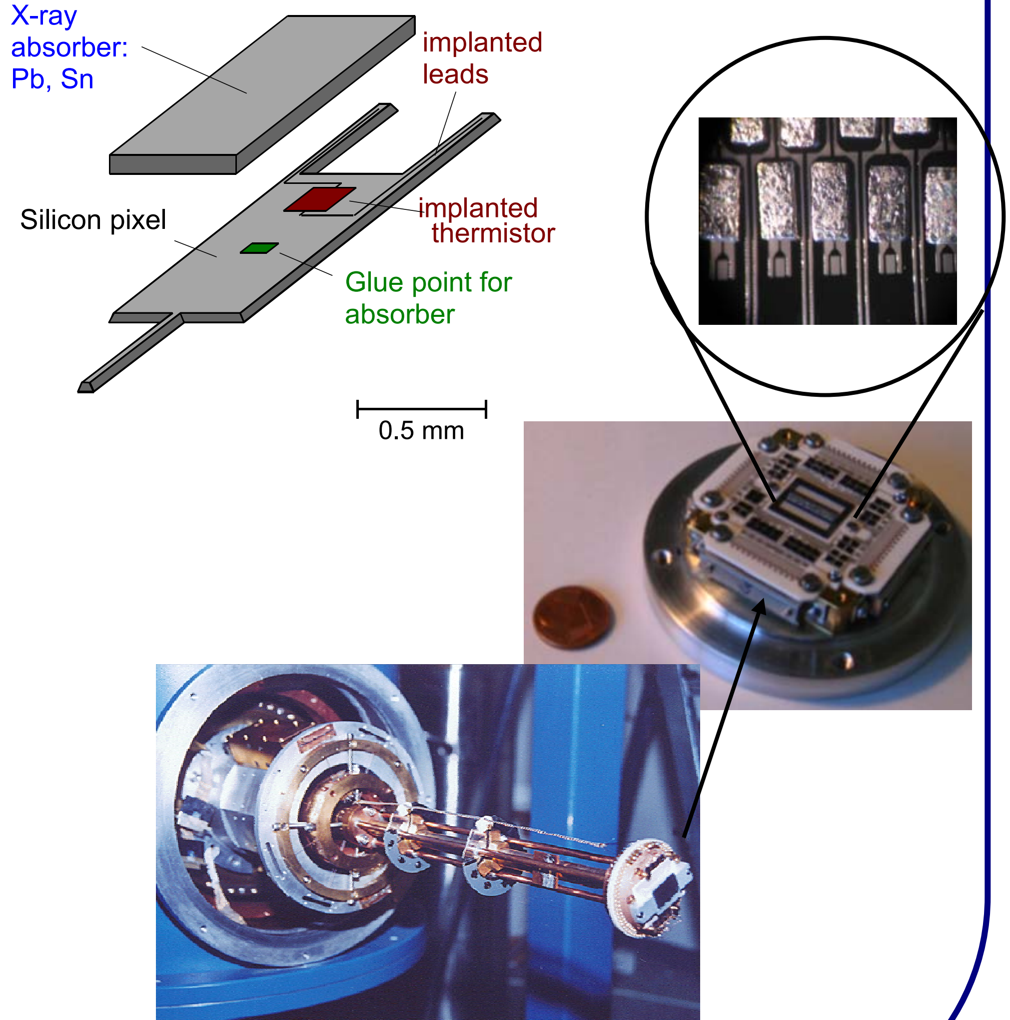
- ➢ $T_A \leq 60$ mK

Absorbers:

- superconductors for small c
- high Z material
  - ➢ Pb, Sn
  - ➢ absorber thickness: 50 µm

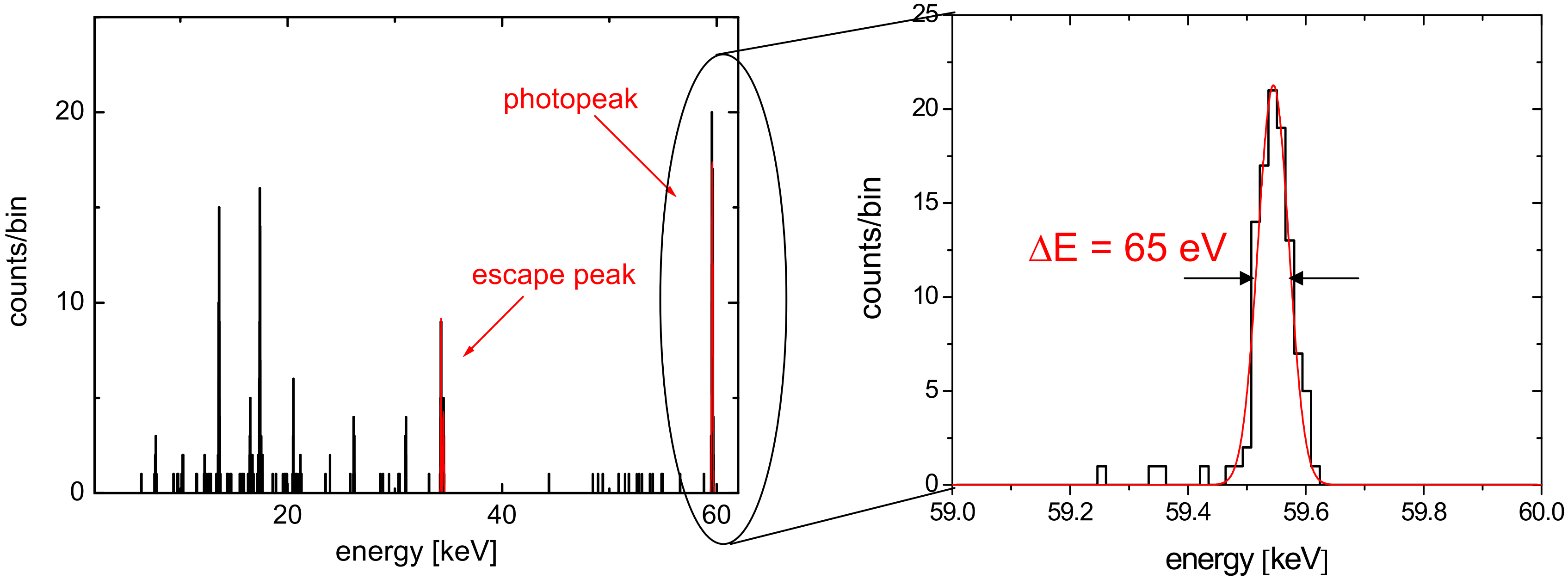
Thermistors:

- large energy range
  - ➢ Si doped with P
- 36 pixel detector array
  - ➢ pixel area 2 x 0.5 mm²
- developed and fabricated by Madison / Goddard group



Performance of Prototype Array: Energy Spectrum

Energy spectrum obtained for a ^{241}Am source with an Sn absorber (0.3 mm² x 66 µm)



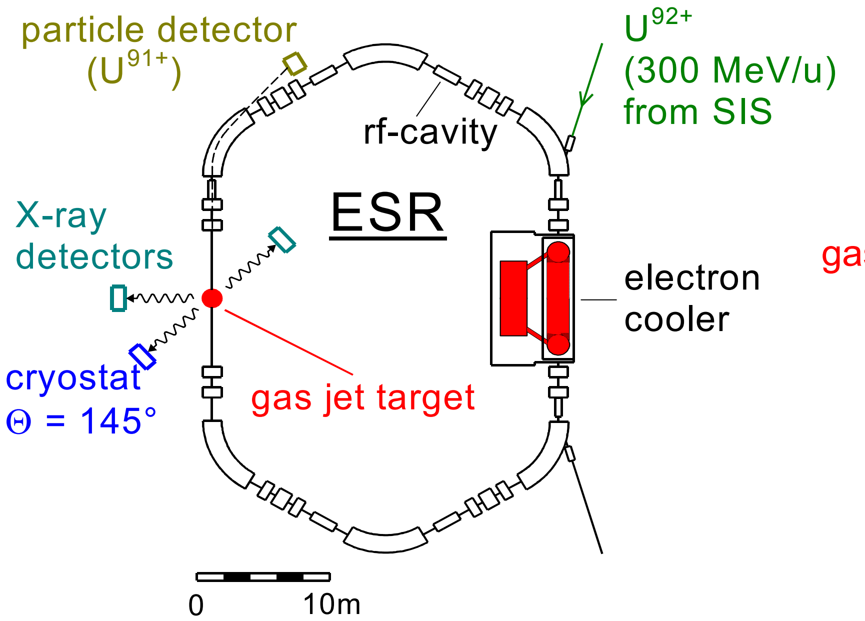
energy resolution at E = 59.5 keV: ΔE = 60 – 65 eV for Sn and Pb absorbers
for comparison:
theoretical limit for a conventional semiconductor detector: $\Delta E_{FWHM} \approx 380$ eV

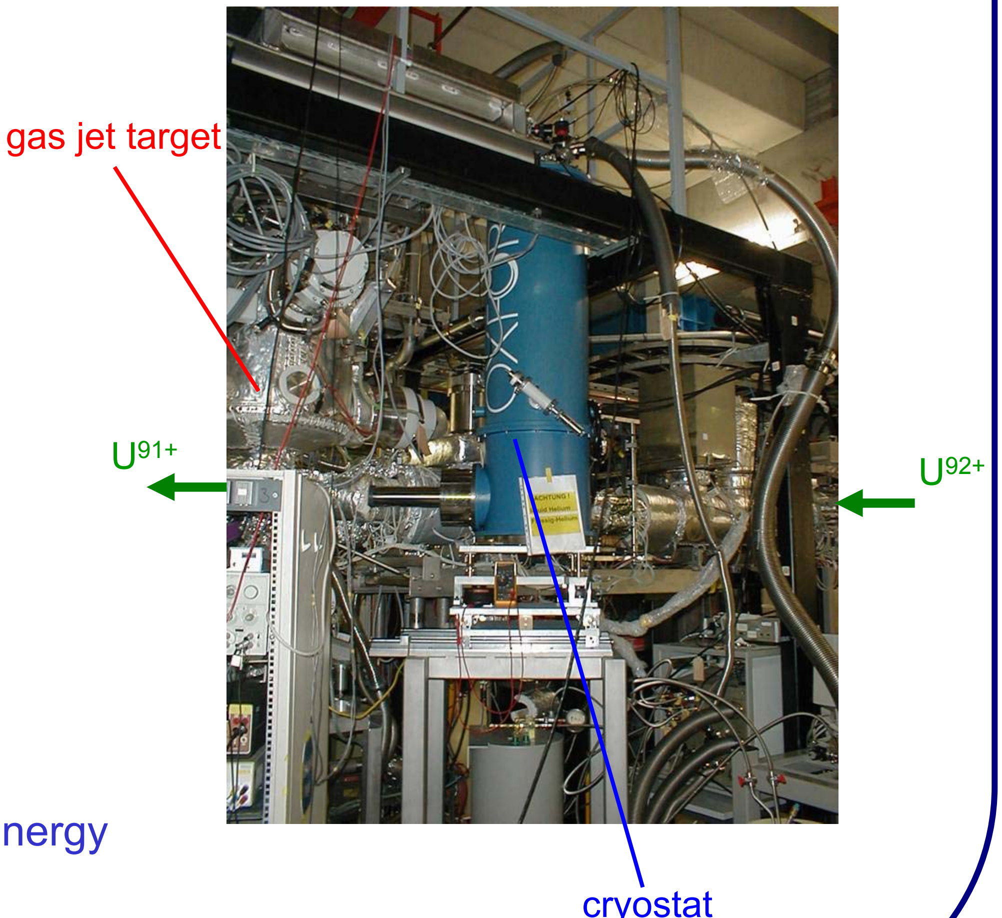
Comparison Between Different Detection Schemes

	Germanium detector	Crystal spectrometer	Calorimeter
Energy resolution	400 eV	60 eV	60 eV
Total efficiency	$10^{-3} – 10^{-4}$	10^{-7}	10^{-5}
Dynamic range	large	small	large

In principle, with arrays of several hundred pixels, also for calorimeters an efficiency of $10^{-3} – 10^{-4}$ can be obtained.

VI. The Lamb Shift Experiment at the Experimental Storage Ring (ESR)



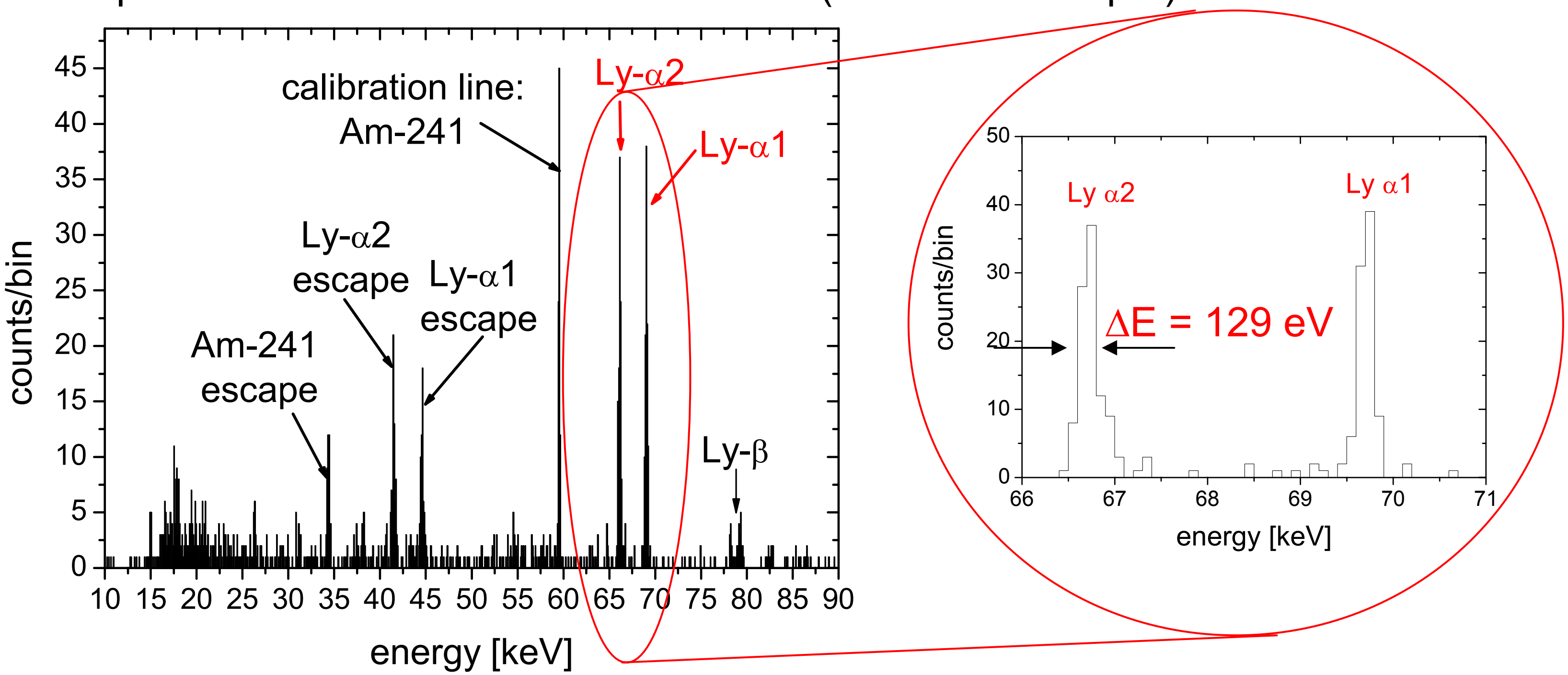


- injection of fully stripped U^{92+} ions
- beam cooling and deceleration
- electron capture in the gas target
- detection of the Lyman-α-radiation
- transformation of measured Lyman-α energy into laboratory frame

First Test: Measurement on $^{238}U^{91+}$

- beam: $^{238}U^{92+}$ at E = 89 MeV/u ⇒ Doppler broadening ΔE_D = 80 eV
- total measurement time 50 h

Spectrum obtained with an Sn absorber (0.39 mm² x 85 µm):

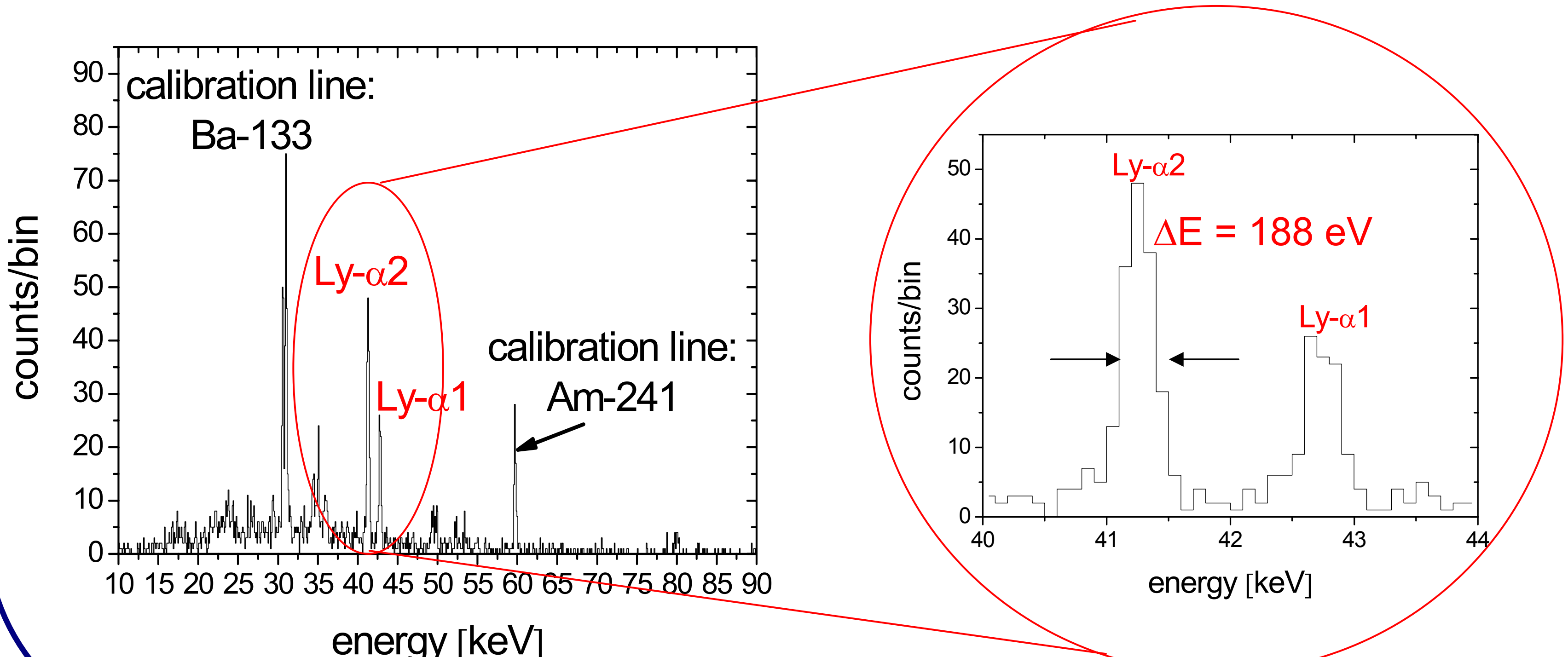


- Lyman-α lines unambigously identified
- achieved energy resolution: ΔE = 129 eV

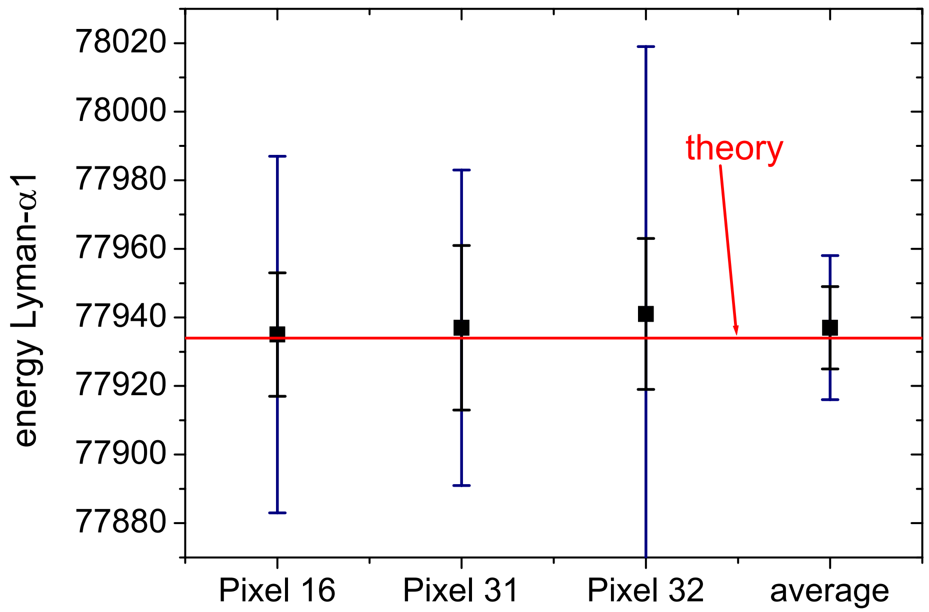
First Experiment for Lamb Shift Measurement on $^{207}Pb^{81+}$

- joint experiment with crystal spectrometer FOCAL
- beam: $^{207}Pb^{82+}$ at 219 MeV/u ⇒ Doppler broadening ΔE_D = 160 eV
- test array with 3 pixels
  - overall detection efficiency: 2.5×10^{-7}

Best Spectrum obtained with an Sn absorber (0.41 mm² x 85 µm):



Results: Summary



- Result: **E(Ly-α1) = (77937 $\pm$ 12$_{stat}$ $\pm$ 25$_{syst}$) eV**
- within error bars: good agreement between experiment and theory
- precision dominated by systematic errors due to
  - ➢ non-linear energy calibration
  - ➢ uncertainty in exact position of detector and gas jet target

V. Conclusion

- Microcalorimeters
  - provide excellent energy resolution of $\Delta E/E = 1 – 4 \times 10^{-3}$ for the detection of x-ray photons at E = 50 – 100 keV

- prototype array with 3 pixels successfully applied in a first experiment at the ESR for $^{207}Pb^{81+}$:
  - overall detection efficiency 2.5×10^{-7}
  - Energy resolution $\Delta E \sim 190$ eV due to Doppler broadening
  - Result: **$E(Ly\text{-}\alpha 1) = (77937 \pm 12_{stat} \pm 25_{syst})$ eV** in good agreement with theoretical prediction

- to improve statistical error: full array with 32 pixels is currently being equipped and tested: $\Delta E = 30 – 40$ eV @ 60 keV

- to improve systematic errors:
  - new calibration source with more lines/ higher intensity
  - decrease Doppler broadening
    - ➔ decelerated beams
    - ➔ new gas-jet target with smaller jet diameter

VI. Perspectives: Microcalorimeters at HITRAP

Application of Microcalorimeters at HITRAP

- Combination with a cold ion trap
  - Optimal utilization of solid angle
  - Minimization of systematic uncertainties due to pixel/gas jet position

Scientific topics:

- Hard X-rays: E ~ 100 keV

  Determination of Lamb shift on H-like ions with precision better than 1 eV
  - Measurement of stable nuclides: precise test of QED
  - Measurement of unstable nuclides: Determination of nuclear charge radii

  Investigation of Beryllium-like ions: inner-shell vacancies
- Soft X-rays: E ~ 1 – 5 keV

  Measurement of Li-like ions: Physics in 3-electron-systems
- Combined X-ray and laser spectroscopy
  - Simultanous measurement of optical and X-ray transitions
  - Calibration of optical measurements of long isotope chains
- Measurements of unstable nuclides with crystal spectrometers not possible due to very low detection efficiency!