Report on Cryogenic Micro-Calorimeter Detectors in High-Precision X-Ray Spectroscopy Experiments at GSI/FAIR

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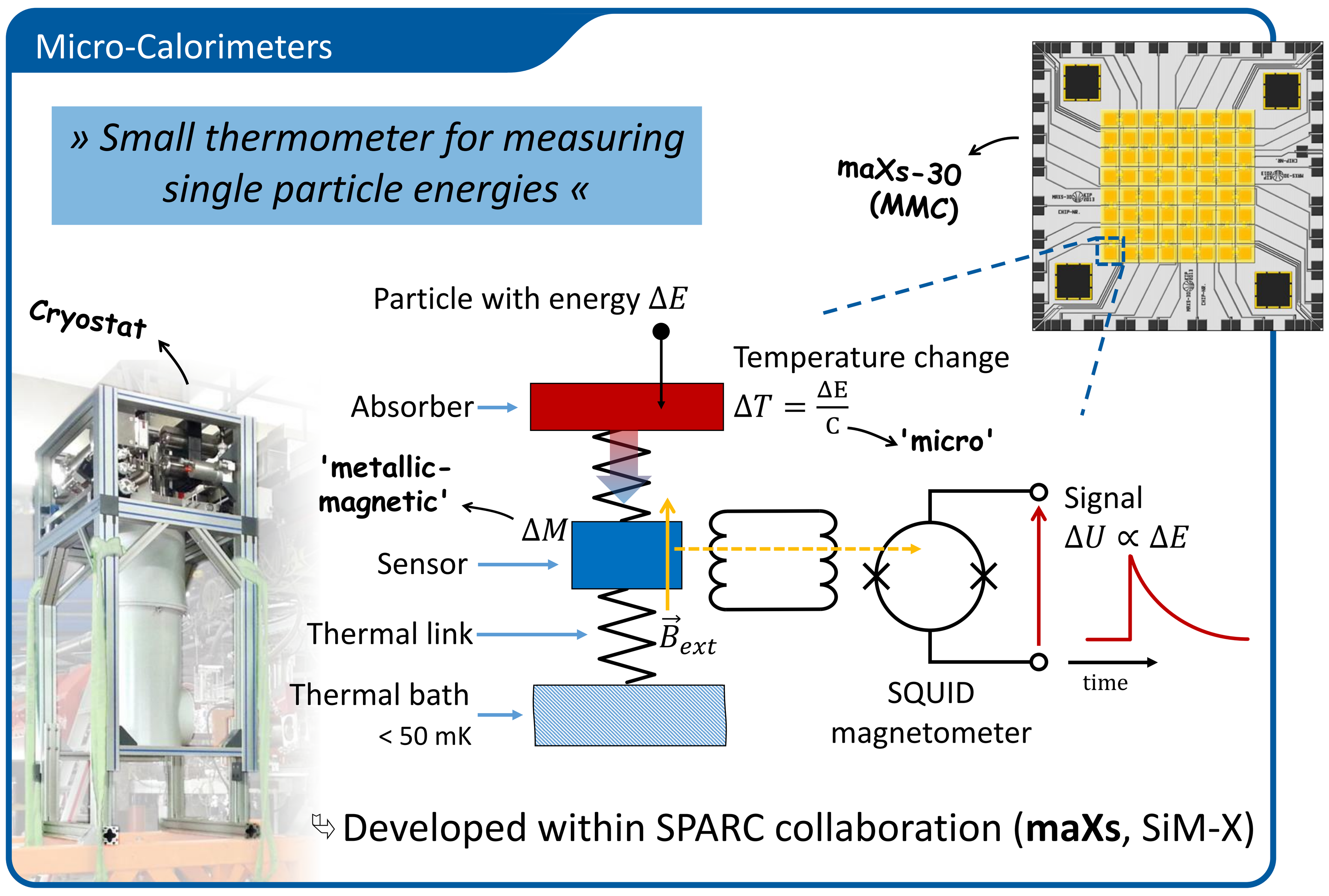
Micro-Calorimeters

» Small thermometer for measuring single particle energies «



➪ Developed within SPARC collaboration (**maXs**, SiM-X)

Motivation

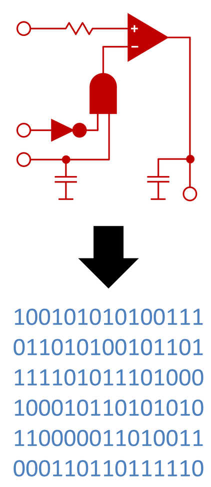
Outstanding properties associated with MMCs [1,2,3]:

- Fast signal rise time up to $\tau_0 \approx 100$ ns
- High energy resolution ΔE_{FWHM} = 1.6 eV @ 6 keV
- Excellent linearity ΔE / E < 5.9% @ 60 keV

However: Best performance is only achievable …
… with a transition **Analog** ⇒ **Digital** signal processing

MMC is **susceptible to environmental** changes…
…vibrations, magnetic flux, etc. ⇒ **corrections needed**

Development of a complex signal analysis framework
➪ Test and improvement through **experiments**



Experiments and Results

10 keV electron beam on Fe [4]

2018 – 2019,
S-EBIT-I, 90°,
maXs-30

Proof of principle experiment
⇒ Continuous MMC operation 9+ months ✔
➪ See related publications

50 MeV/u Xe^{54+} on Xe [5]

August 2014
ESR of GSI
gas-target, 60°
maXs-200

Symmetrical heavy systems + low energy
Electrons transfered from target to projectile
NRC and electron hole production
⇒ Radiation from relaxation of excited states

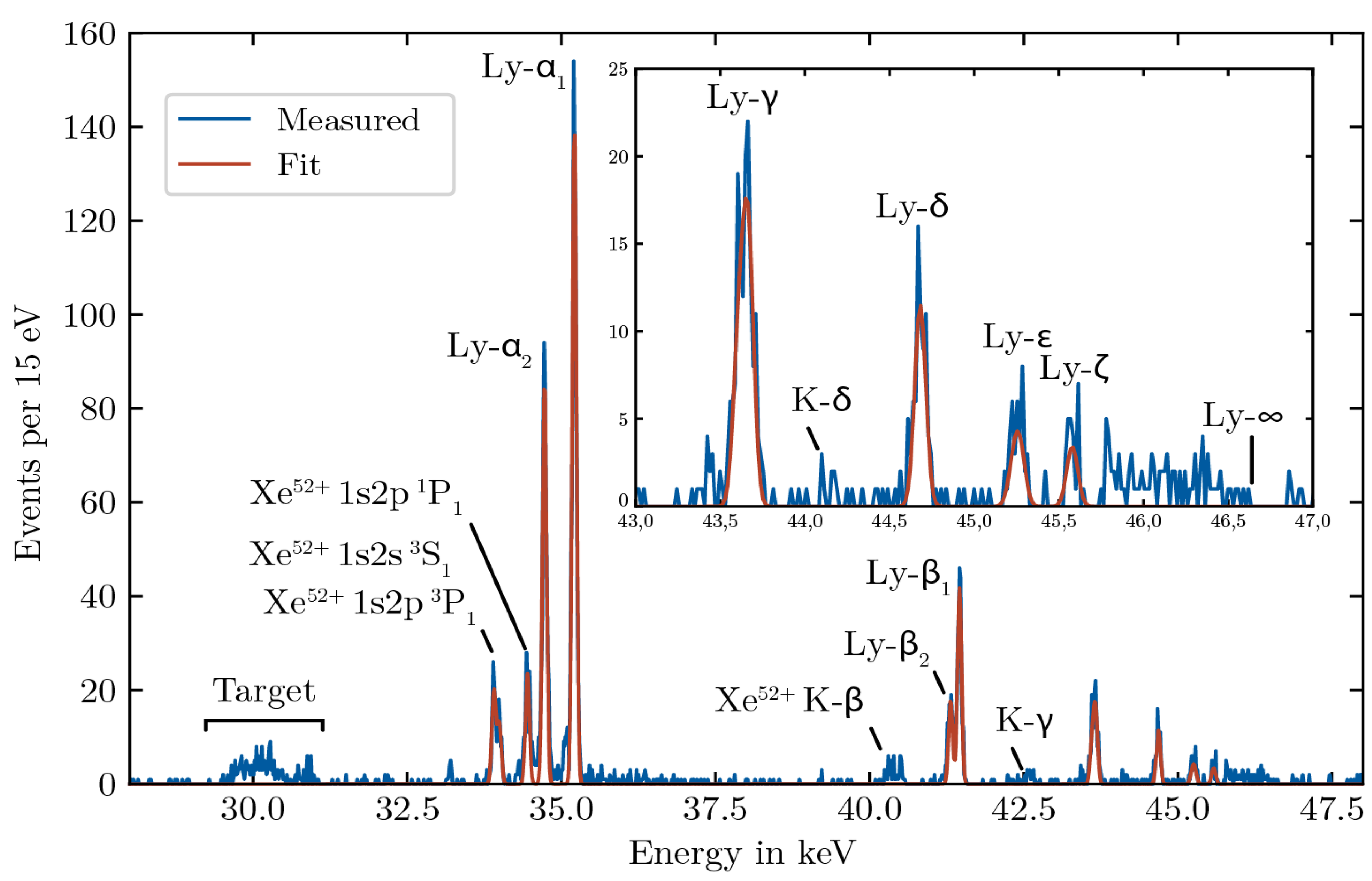
Transition Xe^{53+}	E_i [eV] Theory P. Indelicato	$E_i - E_f$ [eV] Experiment Emit. system
$2p_{3/2} \to 1s_{1/2}$	−10 015.94	31 284.00(287)
$3p_{1/2} \to 1s_{1/2}$	−4 593.26	36 706.28(452)
$3p_{3/2} \to 1s_{1/2}$	−4 466.24	36 833.79(370)

uncertainty from fit-error and Doppler corr.

$$(E_i - F_f)_{exp} = f \cdot (E_{i,theo} - E_f)$$

Linear fit of transition to excited state eneries
Doppler correction f by consideration of multiple lines
1s-Lamb-Shift in Xe^{53+} from ground state E_f ⇒ E_{LS} = 46.87(278) eV
➪ Excellent agreement with theory (47.09 eV, Indelicato p.c.) ✔

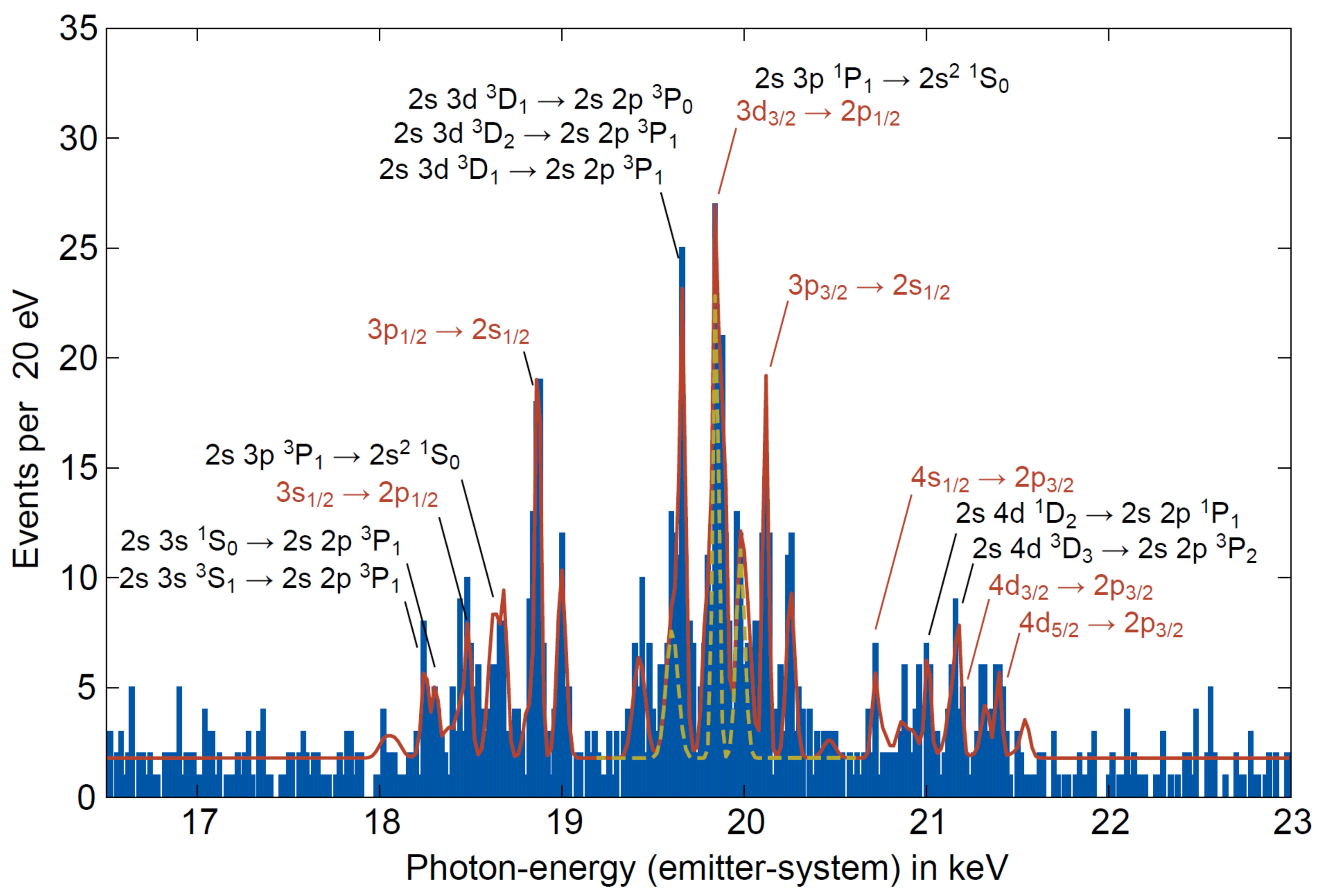
Transition Xe^{52+}	Experiment [eV] Emit. System	Δ Theory[eV] Johnson	Drake	Artemyev
1s 2s $^3S_1$ → 1s^2 $^1S_0$	30 124.68(285)	4.42	3.71	4.46
1s 2p $^3P_1$ → 1s^2 $^1S_0$	30 203.50(317)	2.70	2.08	2.77



76 MeV/u U^{89+} on N_2 [6]

June 2016
ESR of GSI
gas-target, 90°
maXs-30

Excitation ⇒ U^{89+} and electron capture ⇒ U^{88+}
Subsequent transitions into and within L-shell
Satellite artifacts due to fluctuating op. point
⇒ Fit each peak with two side-peaks to get energies



Transition U^{89+}	$E_i - E_f$ [eV] Theory FAC	$E_i - E_f$ [eV] Experiment Emit. system
$3d_{3/2} \to 2p_{3/2}$	15 657.7	15 660.6(64)
$3d_{3/2} \to 2p_{1/2}$	19 841.7	19 844.1(34)
$3p_{3/2} \to 2s_{1/2}$	20 113.1	20 117.6(38)
$3p_{1/2} \to 2s_{1/2}$	18 862.7	18 868.7(35)

uncertainty from counting statistics + Doppler corr.

Use transitions $\Delta E(3d_{3/2} \to 2p_{1/2}) - \Delta E(3d_{3/2} \to 2p_{3/2})$ + L-Intrashell
⇒ 2s-Lamb-Shift in U^{89+} amounts to E_{LS} = 276.4(74) eV
➪ Good agreement with theory (280.76(14) eV, Yerokhin *et al.*) ✔

E138 - 10 MeV/u U^{91+} on electron beam [7]

May 2021
CRYRING@ESR
e⁻ cooler, 0°+180°
maXs-100

Line-splitting in $K\alpha_1$ and $K\alpha_2$ of He-like Uranium
Relativistic electron-electron interaction
➪ See Poster by Ph. Pfäfflein

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[4] M.O. Herdrich *et al.*, X-Ray Spectrometry **49**, 184-187 (2020)
[5] M.O. Herdrich *et al.*, Eur. Phys. J. D, *submitted* (2023)
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[7] Ph. Pfäfflein *et al.*, Phys. Scr. **97**, 0114005 (2022)