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High-Temperature α-Spectroscopy with Diamond-based Detectors

7th ADAMAS Workshop, Vienna, AT – 13th/14th December 2018

Transactinide Elements (TANs)

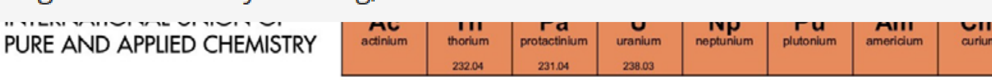
IUPAC ANNOUNCES THE NAMES OF THE ELEMENTS 113, 115, 117, AND 118

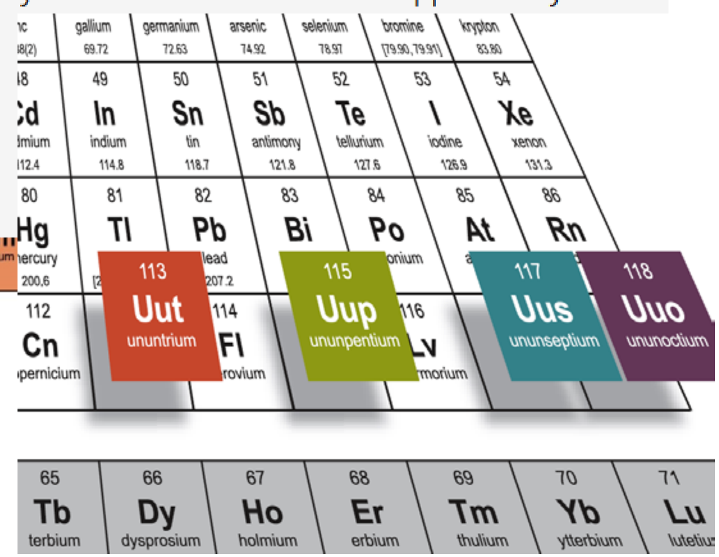
30 November 2016

Elements 113, 115, 117, and 118 are now formally named nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og)

Research Triangle Park, NC: On 28 November 2016, the International Union of Pure and Applied Chemistry (IUPAC) approved the name and symbols for four elements: nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og), respectively for element 113, 115, 117, and 118.

Following a 5-month period of public review, the names earlier proposed by the discoverers have been approved by the IUPAC Bureau. The following names and symbols are officially assigned:
Nihonium and symbol Nh, for the element 113,
Moscovium and symbol Mc, for the element 115,
Tennessine and symbol Ts, for the element 117, and
Oganesson and symbol Og, for the element 118.





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Transactinide Elements (TANs)

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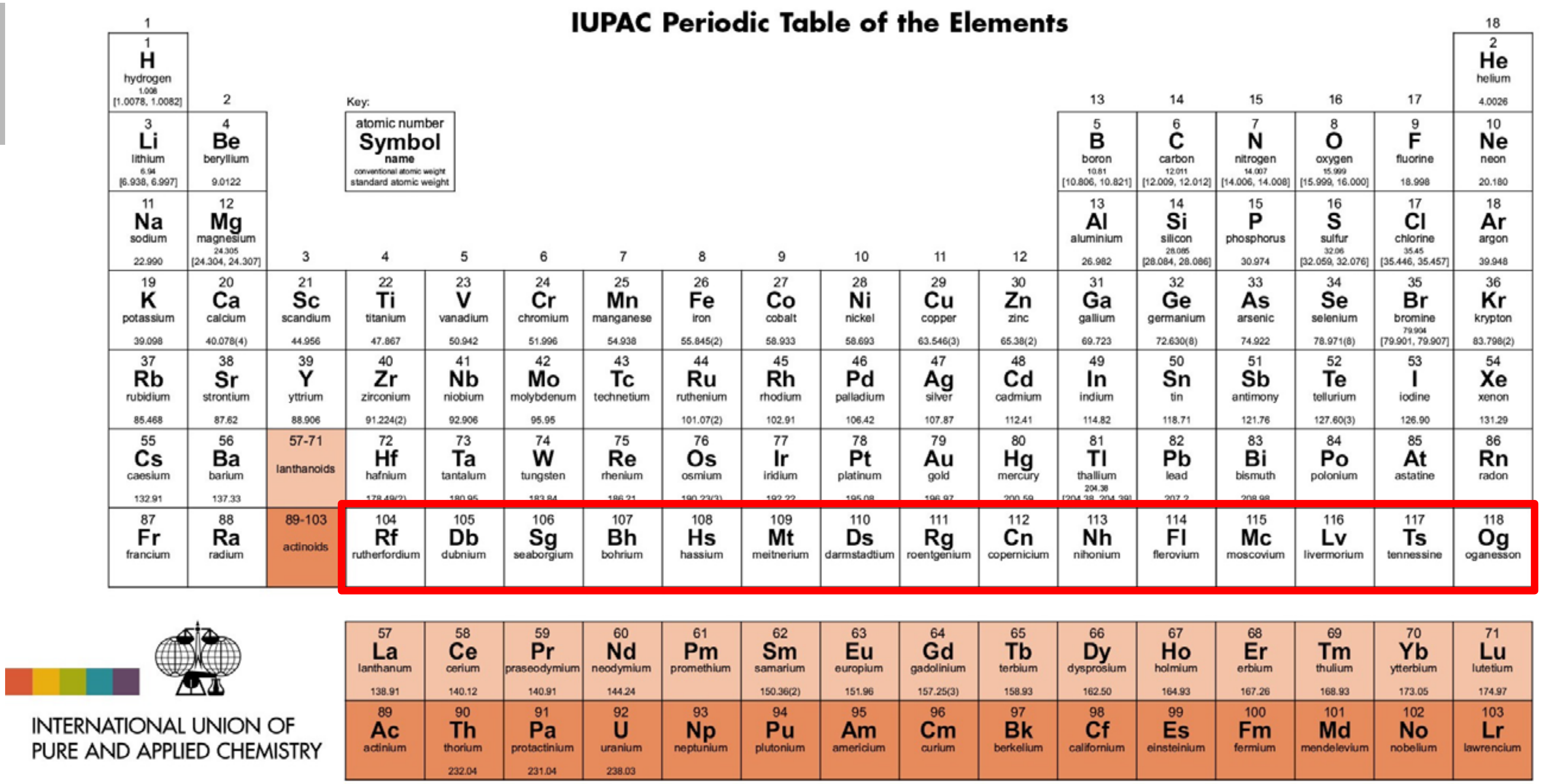
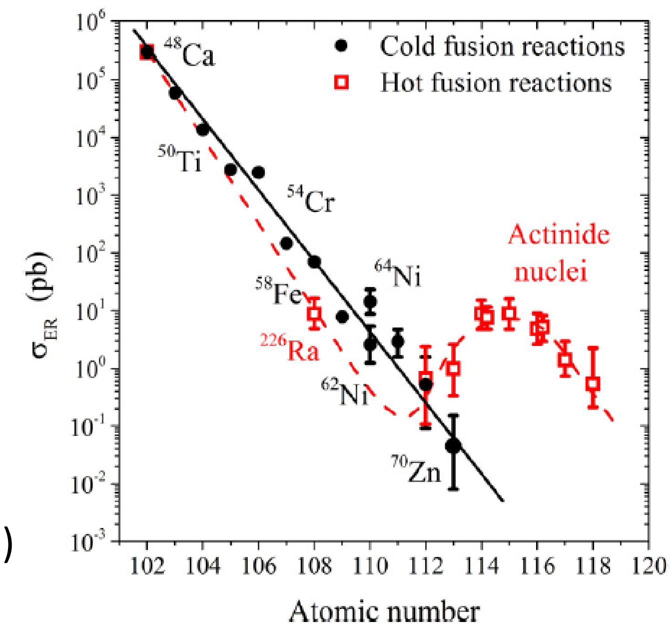


Production of TANs

- Artificial elements
  - Not observed in nature so far
  - Production: heavy-ion-induced fusion reactions
    - Hot and cold fusion reactions
    - Cross sections: nb to pb
    - Record: $^{209}Bi(^{70}Zn, n)^{278}Nh \rightarrow \approx 22^{+20}_{-13}$ fb [1]
      (3 observed atoms in 553 days of beam time)
    - «Standard» projectile: ^{48}Ca
  - Production rates: atoms/min to atoms/month (or less)
  - Short half-lives: single hours to microseconds
  - Currently: 111 isotopes of 15 elements



[1] Morita, K. et al. J Phys Soc Jpn **2012**, *81* (10), 1-4

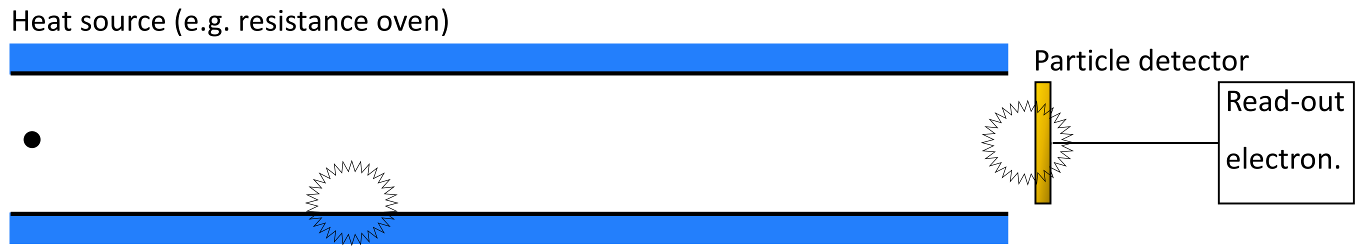
Requirements for Chemical Experiments

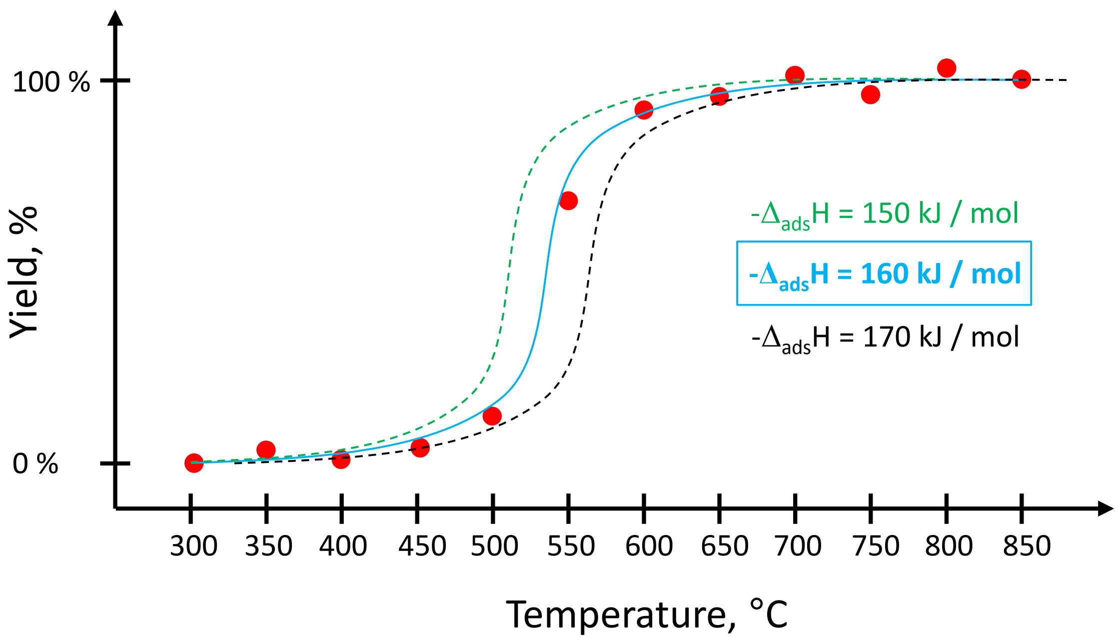
- Speed
- High efficiency
- Sensitive detection of radioactive decay
- Formation of defined chemical states
- Excellent separation of interfering by-products

- «One-atom-at-a-time» chemistry:
  - Single atoms: probabilities instead of equilibrium concentrations
    - Multiple interactions in «chromatographic» systems

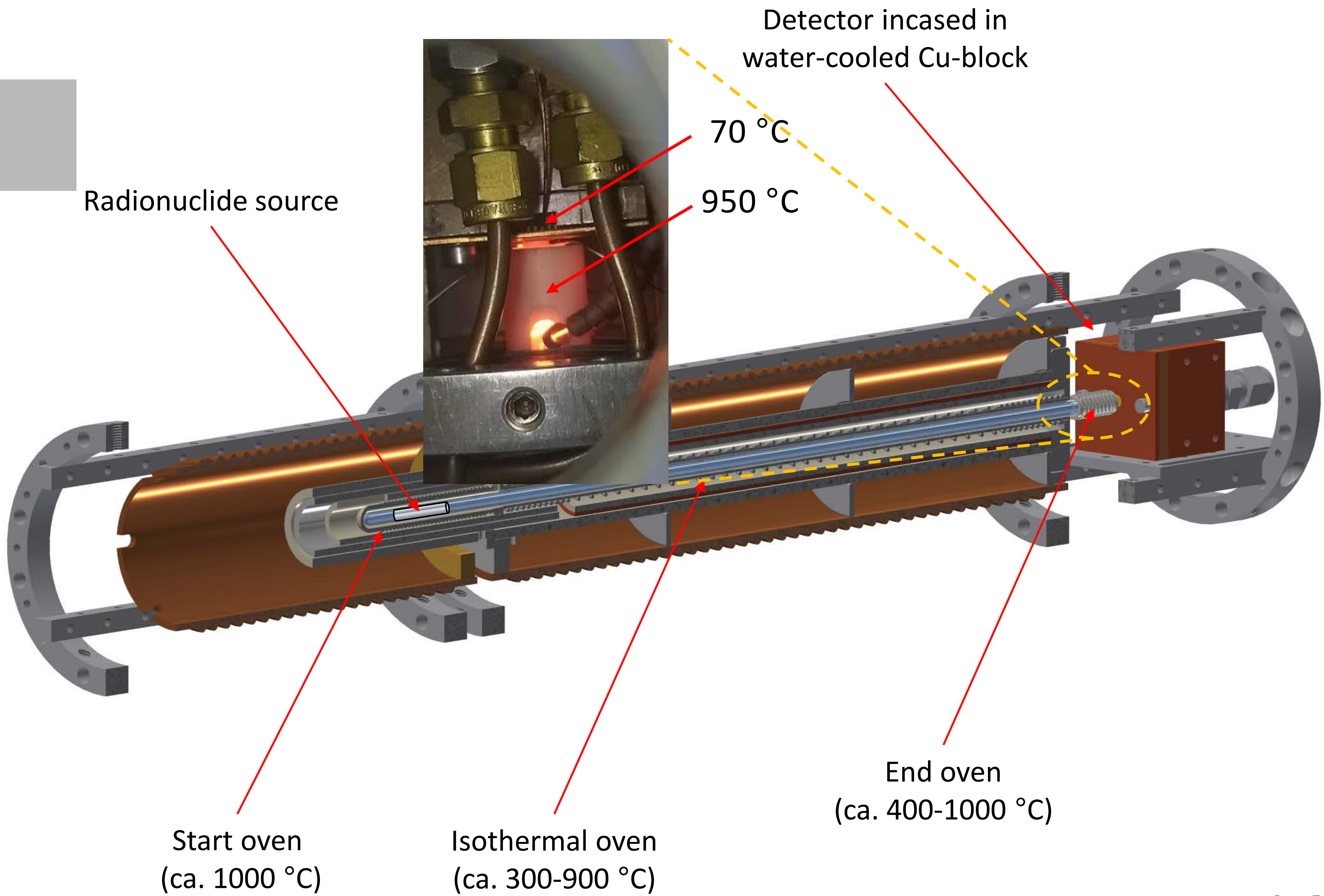
- TAN research: gas chromatography to investigate adsorption properties ($\Delta_{ads}H$)

Isothermal Vacuum Chromatography (IVAC)



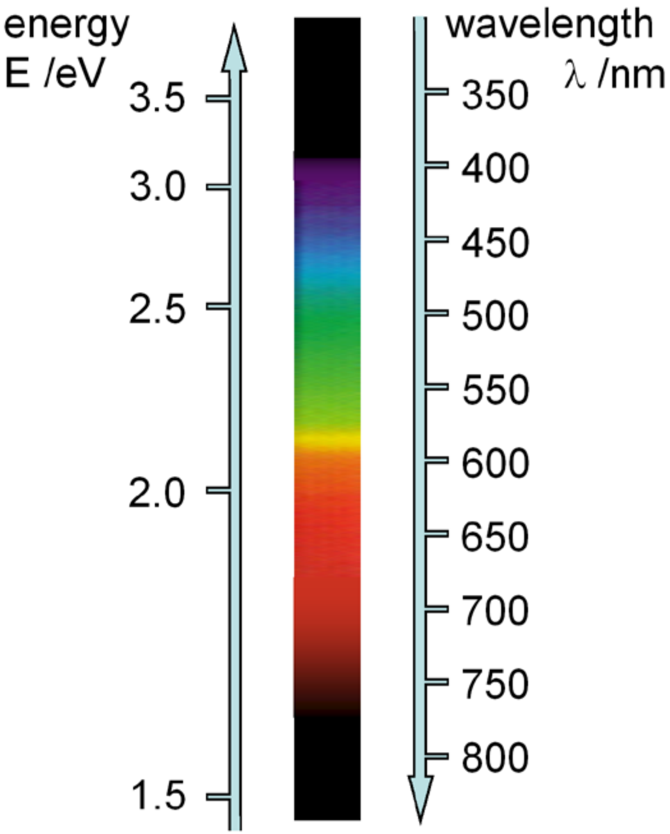


IVAC – Setup


Detector incased in
water-cooled Cu-block
70 °C
950 °C
Radionuclide source
Start oven
(ca. 1000 °C)
Isothermal oven
(ca. 300-900 °C)
End oven
(ca. 400-1000 °C)

Requirements for Sensor Material

- Withstand high temperatures
- Work in high temperature environments
  - Peak shape
  - Energy resolution
- No excitation by UV/vis/IR-radiations
  - Emitted by high temperature heating devices
- Limitations for Si detectors:
  - Complete darkness
  - Temperature ca. 35-40 °C



Promising Wide Band Gap Materials (compared to Si)

Property	Diamond[2]	4H-SiC[2]	Si[2]
Bandgap (eV)	5.5	3.27	1.12
Breakdown field (MV / cm)	10	3.0	0.3
Density (g / cm^3)	3.5	3.2	2.3
e-h creation energy (eV)	13	7.78	3.6
Electron mobility (cm^2 / Vs)	1800-4500	800	1300
Hole mobility (cm^2 / Vs)	1200-3800	115	460
Saturated electron velocity at 300 K (10^7 cm / s)	2.2	2	1.0
Max. Temperature (°C)	200-300[3-4] (1000[5])	375[6]	40-45

[2] Nava, F. et al. *Meas. Sci. Technol.* **2008**, *19*.
[3] Steinegger, P. et al. Nucl Instrum Meth A **2017**, *850*, 61-67.
[4] Kumar, A. et al. Nucl Instrum Meth A **2017**, 858, 12-17
[5] Vescan, A. et al. IEEE Electronic Device Lett. **1997**, *18*, 556-558
[6] Kalinina, E. V. et al., *TePhL* **2008**, *34*, 210-212.

Performance in Hot Environments

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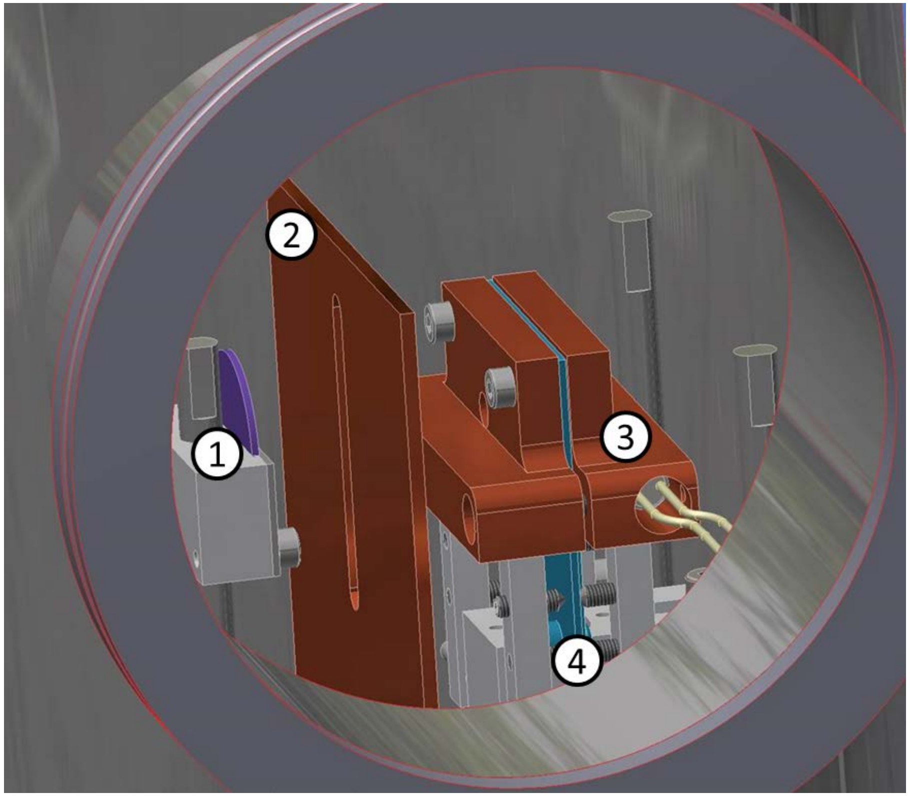
- Diamond sensors in hot environment:
  - high temperature (HT) resistant PCBs

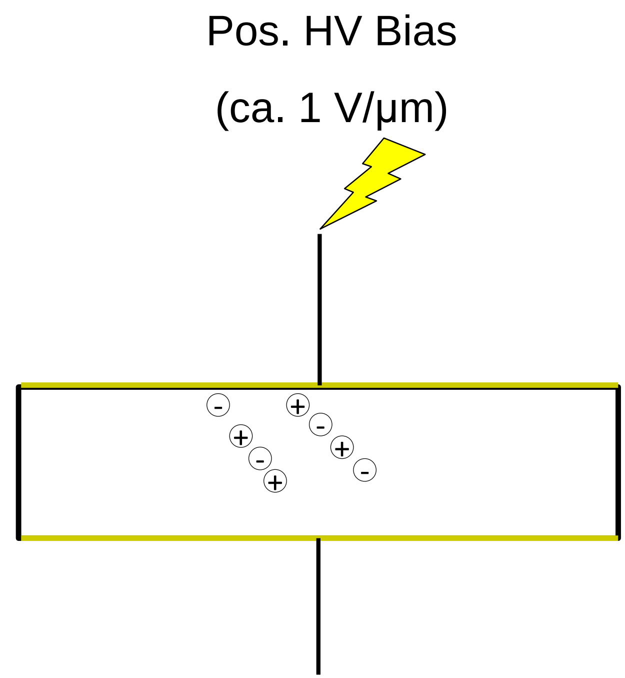
- Investigation:
  - Transient current technique (TCT) measurements
  - Behavior of e^- and h^+ depending on temperature



1 – ^{241}Am source (ca. 25 kBq), **2** – heat shield & collimator, **3** – heat spreader & collimator w/ heating cartridges, **4** – PCB w/ diamond sensor

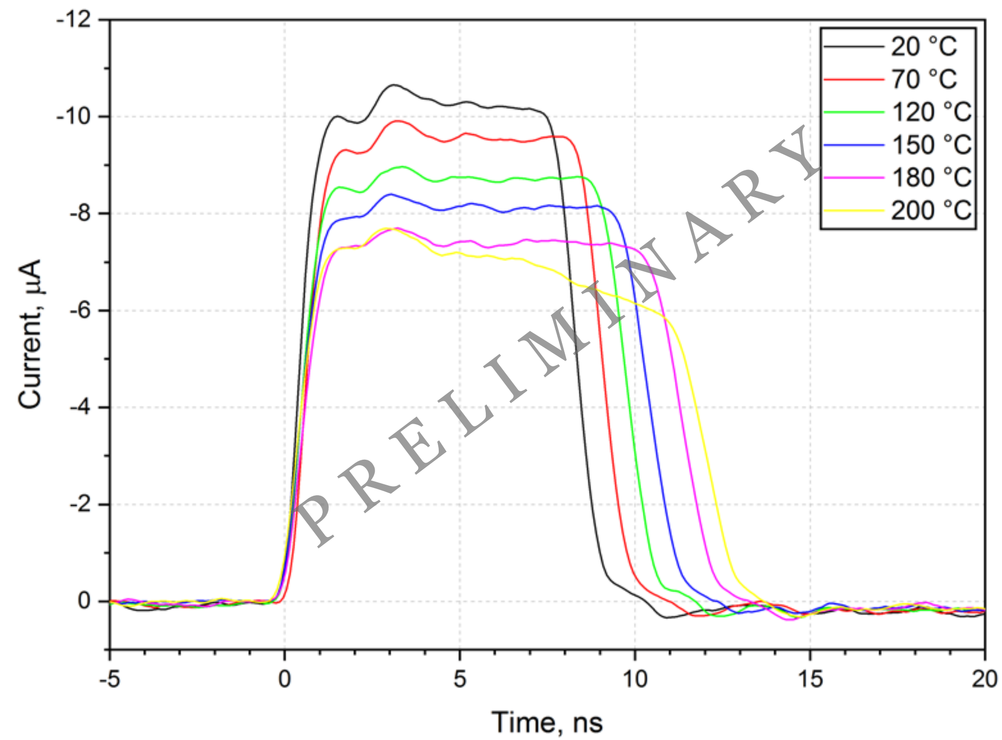
Expected Behavior at High Temperatures

- Amount of charge carriers (e^-/h^+) should be constant
  - α-particles of same energy (^{241}Am: 5486 keV)
- Room temperature:
  - Short transport times
  - Slow lattice vibrations (less hindrance for charge carriers)
- High temperature:
  - Longer transport times
  - Faster lattice vibrations
  - Lower resistance, faster electron transport
  - Recombination of e^- and h^+ more frequently
  - Dark current contributes e^- to recombination



Preliminary Results – TCT

- TCT Measurements:
  - Temp.: 20 °C to 200 °C
  - C2HV0224 Amplifier (43.7 dB = amp.-factor 153.2)
- Electrons:
  - nearly rectangular signals
  - broadening w/ higher temperature
  - area is stays nearly constant



Preliminary Results – TCT

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- Electrons:
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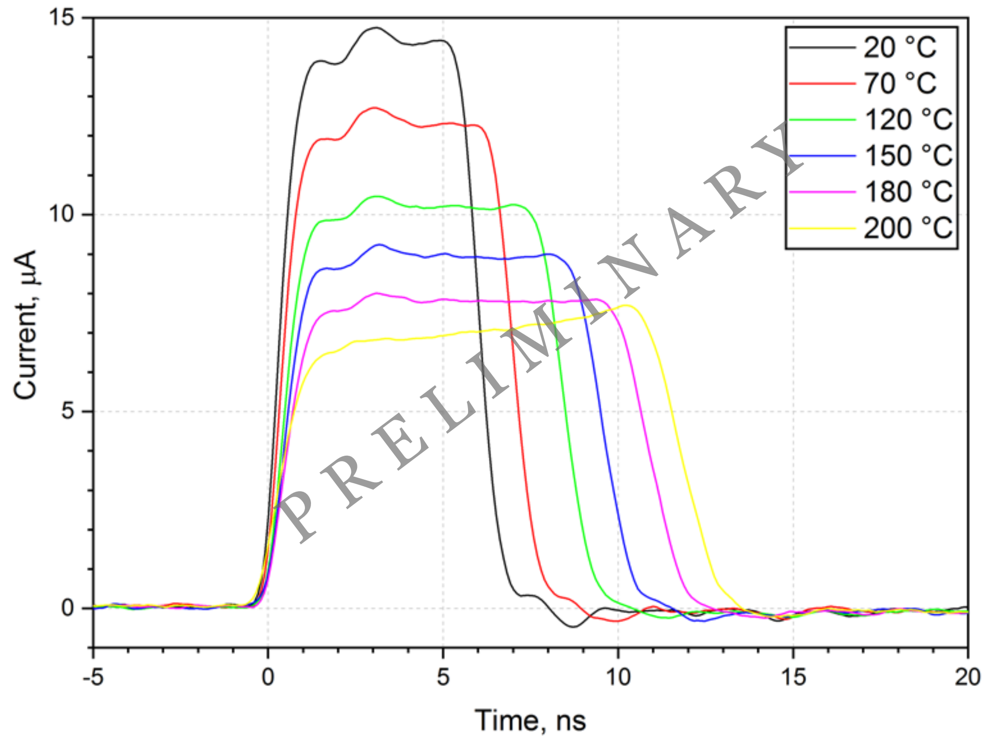
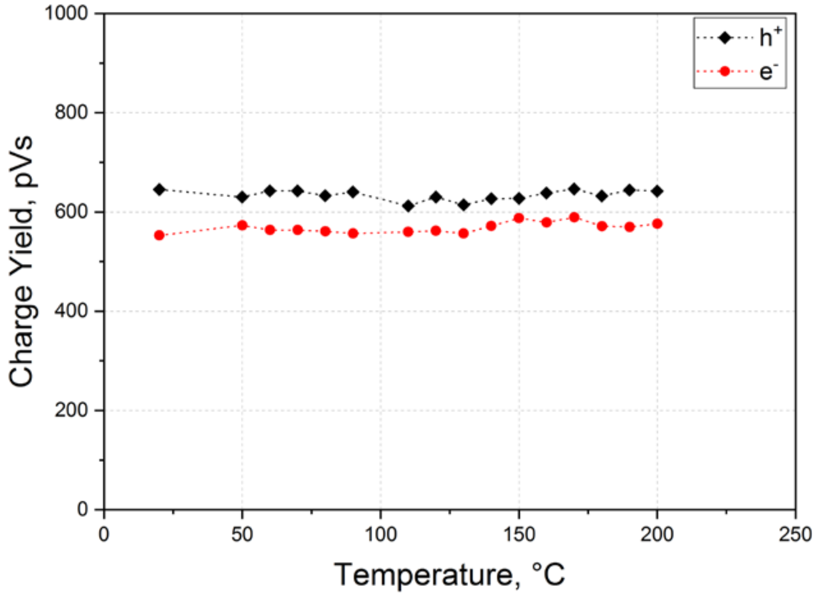
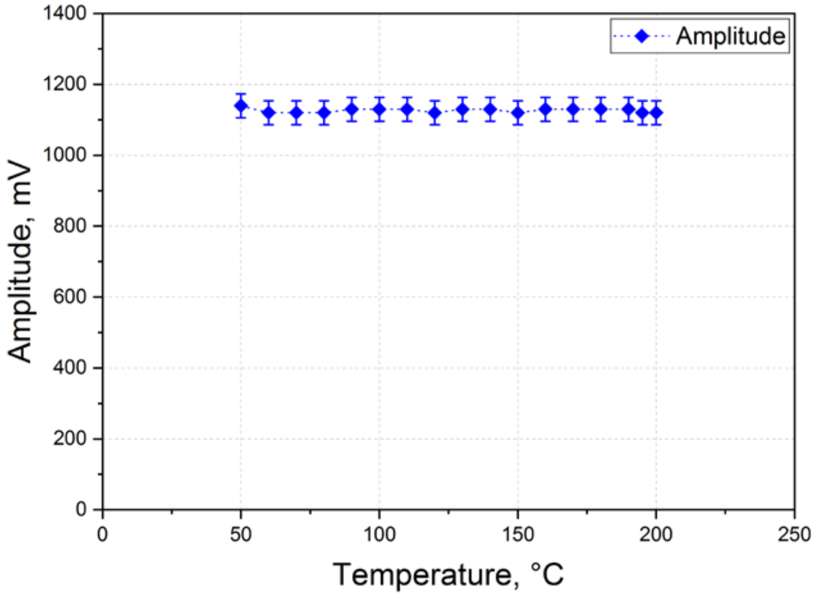
  - broadening w/ higher temperature
  - area is stays nearly constant
- Electron holes:
  - signal form similar to electrons
  - a bit higher and faster



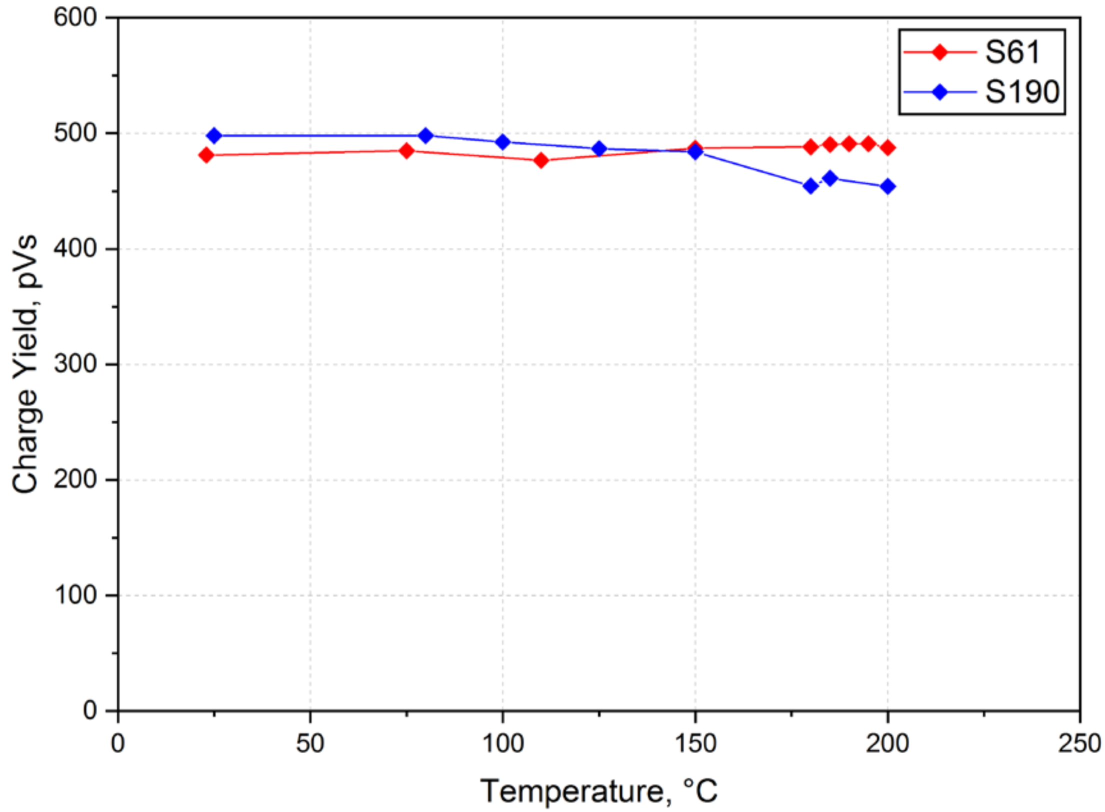
Preliminary Results – Charge Yields & Amplitude





- Constant behavior up to 200 °C:
  - Charge yields (h^+, e^-) (C2 amp.)
  - Mean amplitude (Cx amp.)

Results – Comparison of Two Sensors



- Charge yield comparison of two sensors (S61, S190):
  - Slight differences (<10 %) in the temperature interval up to 200 °C

Outlook

- Further investigation of escCVD diamonds from 200 °C to 500 °C
- Comparative study of escCVD diamond vs. SiC
  - Improving detector design for high temperature
- Envision wide-area detectors for IVAC setups
  - Based on P. Steinegger's previous work
- Replacing current Si detectors with wide band gap detectors
  - Upgrade to work at higher temperatures (goal: 600 °C to 800 °C)
    → thermochromatographic seperator detector array (e.g. COLD)

High-Temperature α-Spectroscopy

- For online measurement of TANs in IVAC:
  - Detector needed to work in vicinity of high temperature and strong IR/vis/UV-radiation

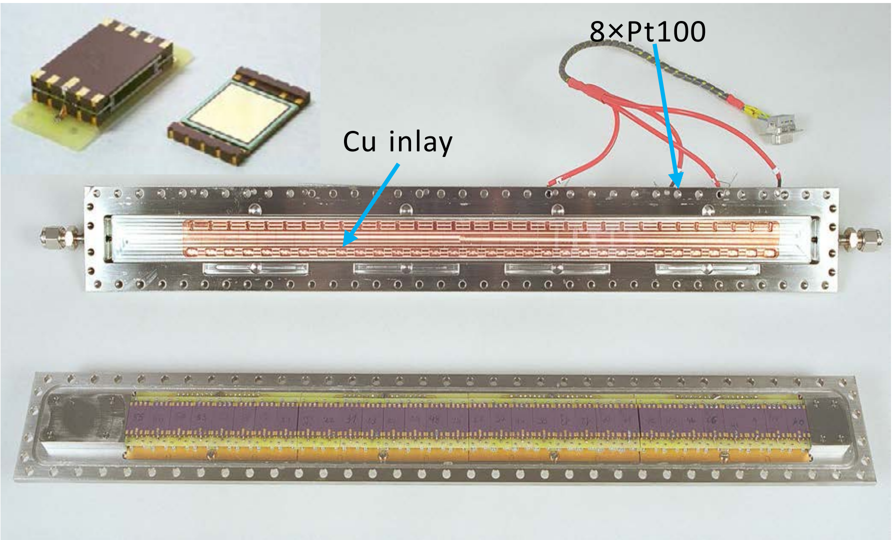
- Wide band gap materials for α-detectors
  - Si requires total darkness (small bandgap: 1.12 eV)
  - Diamond is a wide band gap semiconductor (5.5 eV)

  - SiC also a possible wide band gap semiconductor (3.27 eV)

  → Advantage of SiC: production of electronic grade material
  and much cheaper (ca. 1/1000 of escCVD diamonds)

Implications for TAN Chemistry

- For TAN chemistry: thermochromatographic separator detector arrays
  - PSI: **C**ryo **O**n-**L**ine **D**etector (COLD)
  - GSI: **C**yro-**O**nline-**M**ultidetector for **P**hysics **A**nd **C**hemistry of **T**ransactinides (COMPACT)
  - LBNL: **C**yro-**T**hermochromatographic **S**eperator (CTS)



- With higher temperatures: less volatile elements and compounds accessible

Summary

- «One-atom-at-a-time» chemistry possible due to state-of-the-art detection systems
  - Diamond-based detectors enable high-temperature measurements

- High temperature α-spectroscopy
  - All tested diamonds performed well up to 200 °C
  - Improving detector design for higher temperatures

- Possible explanation for waveform changes:
  - Increased lattice vibration hinders charge carrier transport

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Thank you for your kind attention!

Do you have any questions?