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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.

PURE AND APPLIED CHEMISTRY

Ac	Th	Ra	U	Np	Pu	Am	Cm					
actinium	thorium	protactinium	uranium	neptunium	plutonium	americium	curium					
226.04	231.04	231.04	238.03									
112	113	114	115	116	117	118						
Cn	Uut	Fl	Uup	Lv	Uus	Uuo						
ipernicium	ununtrium	rohrium	ununpentium	morium	ununseptium	ununoctium						

65	66	67	68	69	70	71
Tb	Dy	Ho	Er	Tm	Yb	Lu

Transactinide Elements (TANs)

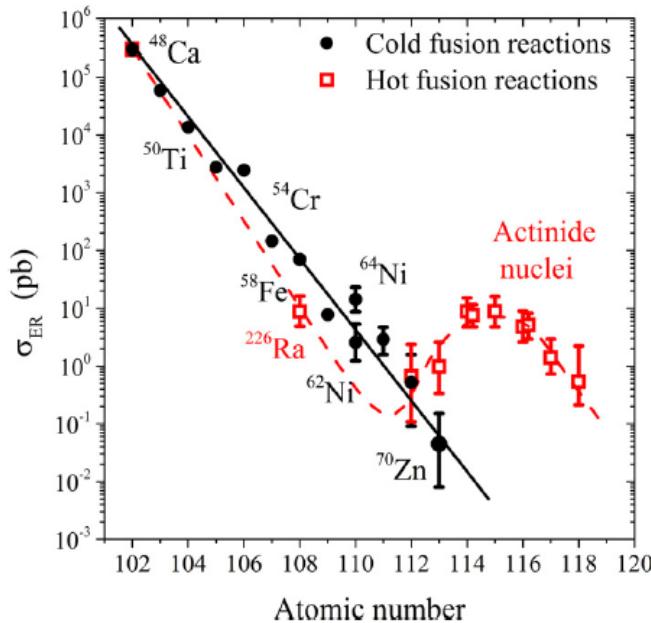
1 1 H hydrogen 1.008 [1.0078, 1.0082]	2 3 Li lithium 6.94 [6.938, 6.997]	4 Be beryllium 9.0122	18 2 He helium 4.0026
11 Na sodium 22.990 [24.305, 24.307]	12 Mg magnesium 24.305 [24.304, 24.307]	13 B boron 10.81 [10.806, 10.821]	14 C carbon 12.01 [12.009, 12.012]
19 K potassium 39.098 40.078(4)	20 Ca calcium 40.078(4) 44.956	21 Sc scandium 47.867	22 Ti titanium 50.942
37 Rb rubidium 85.468 87.62	38 Sr strontium 87.62 88.906	39 Y yttrium 91.224(2)	23 V vanadium 51.996
55 Cs caesium 132.91 137.33	56 Ba barium 137.33 178.49(2)	24 Cr chromium 54.938	25 Mn manganese 55.845(2)
87 Fr francium 88 Ra radium 89-103 actinoids	104 Rf rutherfordium 105 Db dubnium 106 Sg seaborgium 107 Bh bohrium 108 Hs hassium 109 Mt meitnerium 110 Ds darmstadtium 111 Rg roentgenium 112 Cn copernicium 113 Nh nihonium 114 Fl ferrovium 115 Mc moscovium 116 Lv livornium 117 Ts tennessine 118 Og oganesson	26 Fe iron 58.033 58.693 63.546(3) 65.38(2)	27 Co cobalt 58.933 59.693 63.546(3) 65.38(2)
30 Zn zinc 69.723	31 Ga gallium 72.630(8)	32 Ge germanium 74.922	33 As arsenic 78.971(8)
49 In indium 114.82	50 Sn tin 118.71	51 Sb antimony 121.76	52 Te tellurium 127.60(3)
48 Cd cadmium 112.41	49 Ag silver 107.87	50 Pt platinum 106.42	51 Br bromine 79.904 [79.901, 79.907]
80 Hg mercury 200.59 204.38-204.39	81 Tl thallium 202.2 208.98	82 Pb lead 202.2 208.98	83 Bi bismuth 208.98
88 Po polonium 208.98	84 At astatine 212.2	85 Rn radon 212.2	86 Rn radon 212.2
57 La lanthanum 138.91	58 Ce cerium 140.12	59 Pr praseodymium 140.91	60 Nd neodymium 144.24
61 Pm promethium 150.36(2)	62 Sm samarium 151.96	63 Eu europium 157.25(3)	64 Gd gadolinium 158.93
65 Tb terbium 162.50	66 Dy dysprosium 164.93	67 Ho holmium 167.26	68 Er erbium 168.93
69 Tm thulium 173.05	70 Yb ytterbium 174.97	71 Lu lutetium 174.97	
89 Ac actinium 232.04	90 Th thorium 231.04	91 Pa protactinium 238.03	92 U uranium 238.03
93 Np neptunium 239.03	94 Pu plutonium 244.03	95 Am americium 243.03	96 Cm curium 247.03
97 Bk berkelium 249.03	98 Cf californium 251.03	99 Es einsteinium 252.03	100 Fm fermium 253.03
101 Md mendelevium 254.03	102 No nobelium 255.03	103 Lr lawrencium 257.03	

INTERNATIONAL UNION OF
PURE AND APPLIED CHEMISTRY

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Production of TANs

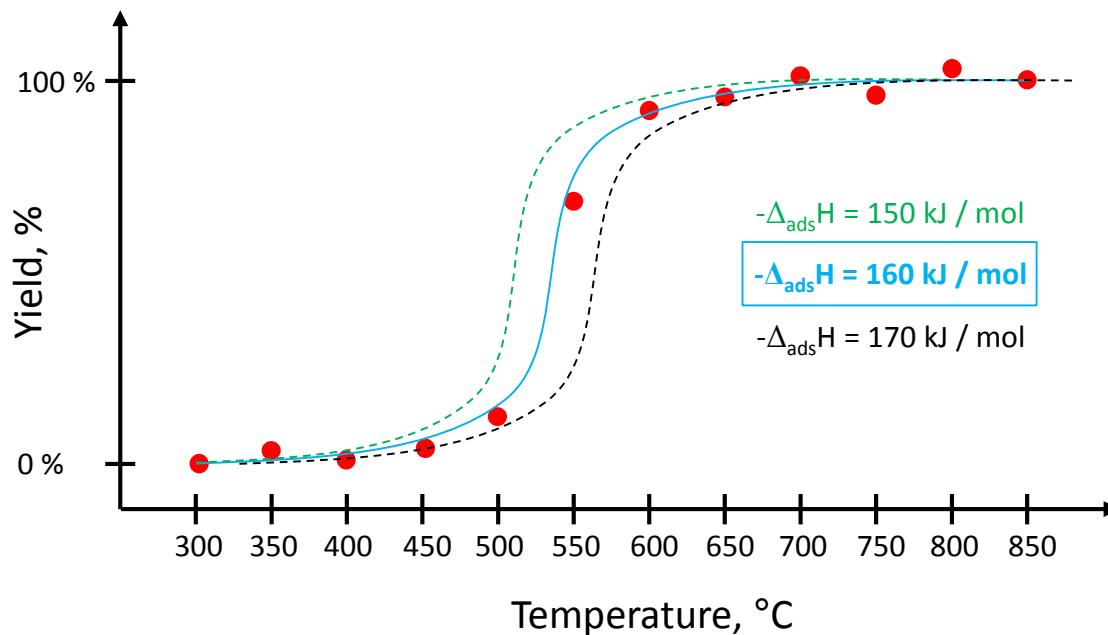
- Artificial elements
 - Not observed in nature so far
 - Production: heavy-ion-induced fusion reactions
 - Hot and cold fusion reactions
 - Cross sections: nb to pb
 - Record: $^{209}\text{Bi}(^{70}\text{Zn}, \text{n})^{278}\text{Nh} \rightarrow \approx 22^{+20}_{-13}$ fb [1]
(3 observed atoms in 553 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

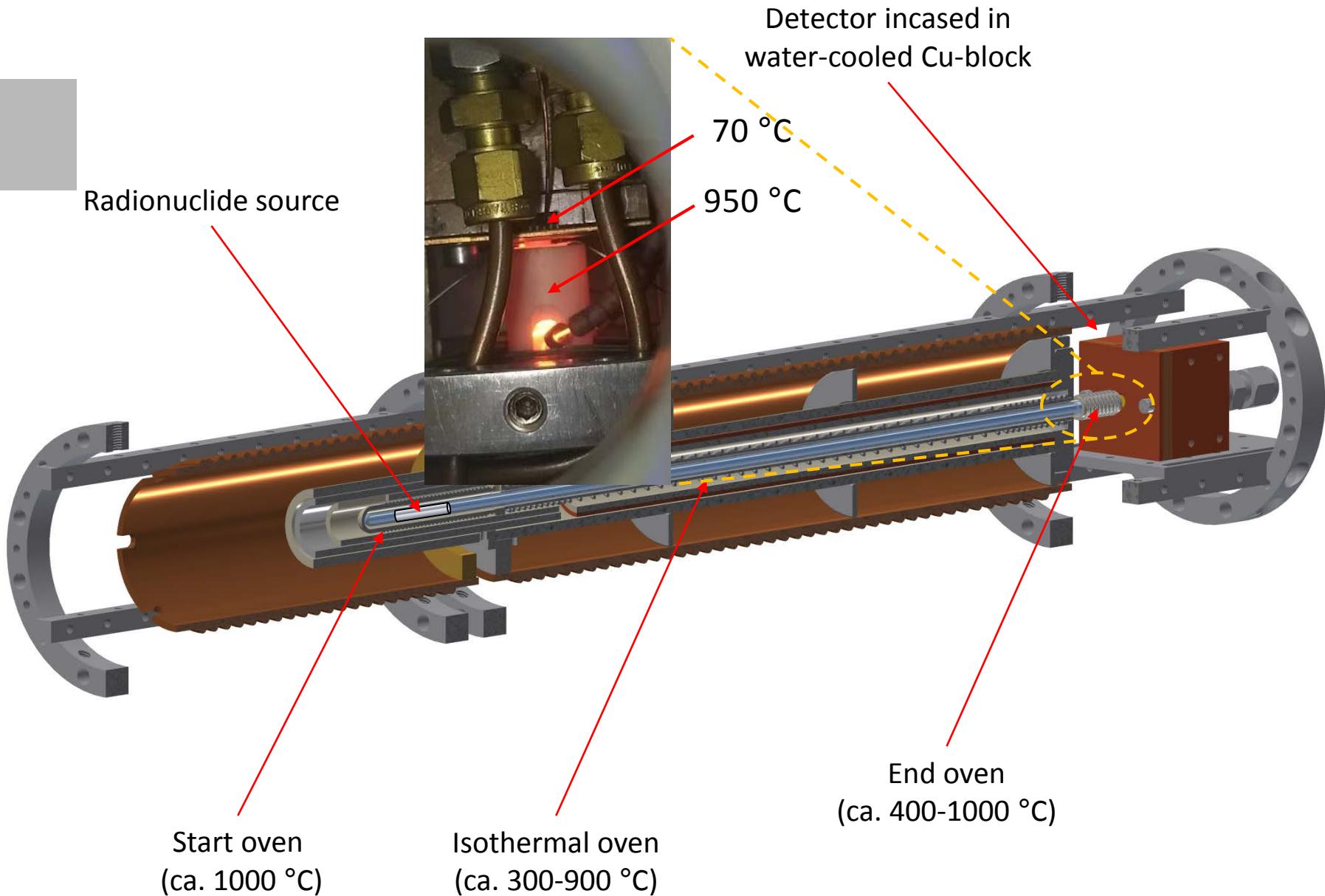


Requirements for Chemical Experiments

- 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 ($\Delta_{\text{ads}}H$)

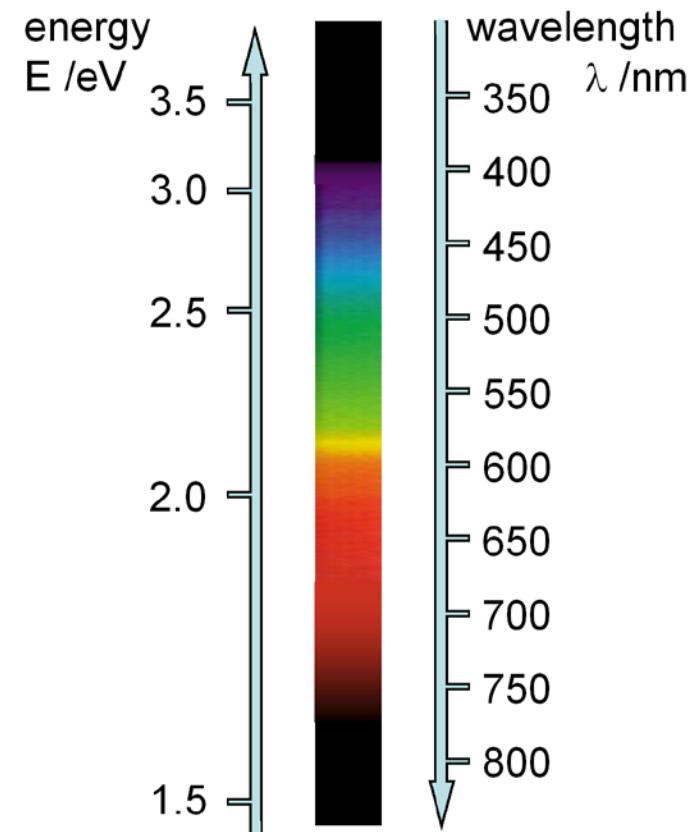
Isothermal Vacuum Chromatography (IVAC)





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

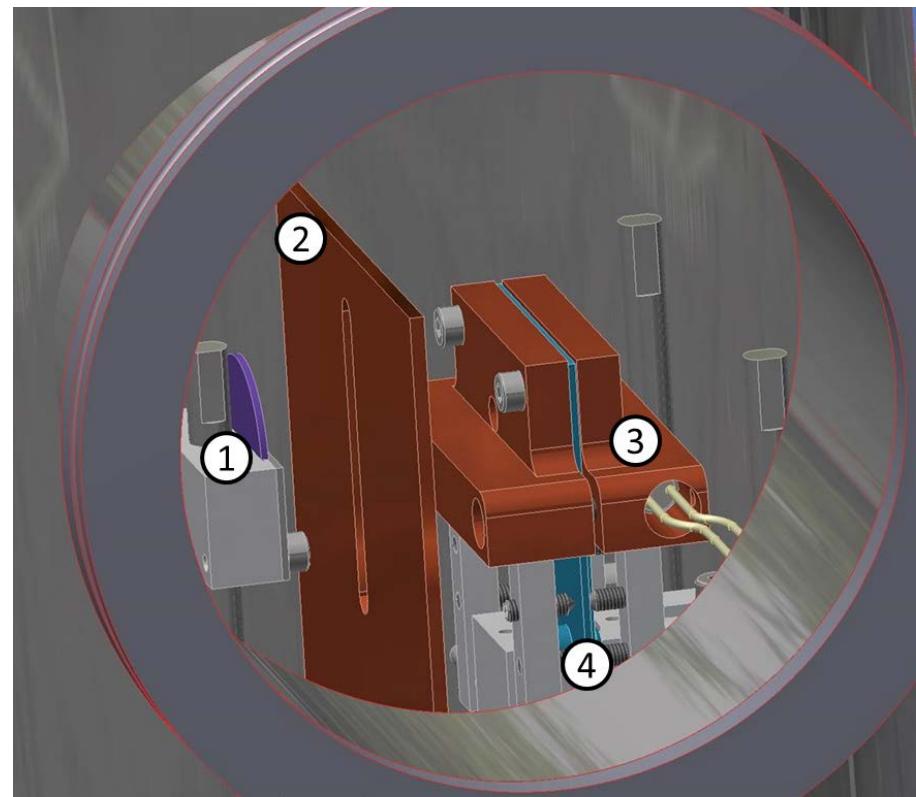


Promising Wide Band Gap Materials (compared to Si)

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.

- Diamond sensors in hot environment:
 - high temperature (HT) resistant PCBs
- Investigation:
 - Transient current technique (TCT) measurements
 - Behavior of e^- and h^+ depending on temperature

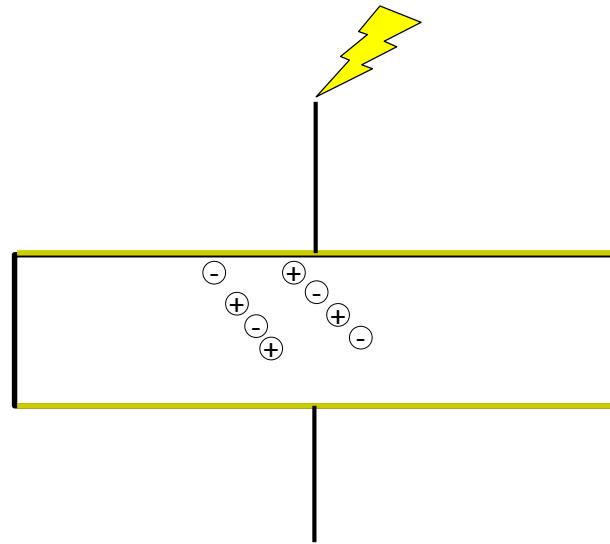


1 – ^{241}Am source (ca. 25 kBq), 2 – heat shield & collimator,
 3 – heat spreader & collimator w/ heating cartridges,
 4 – PCB w/ diamond sensor

- 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

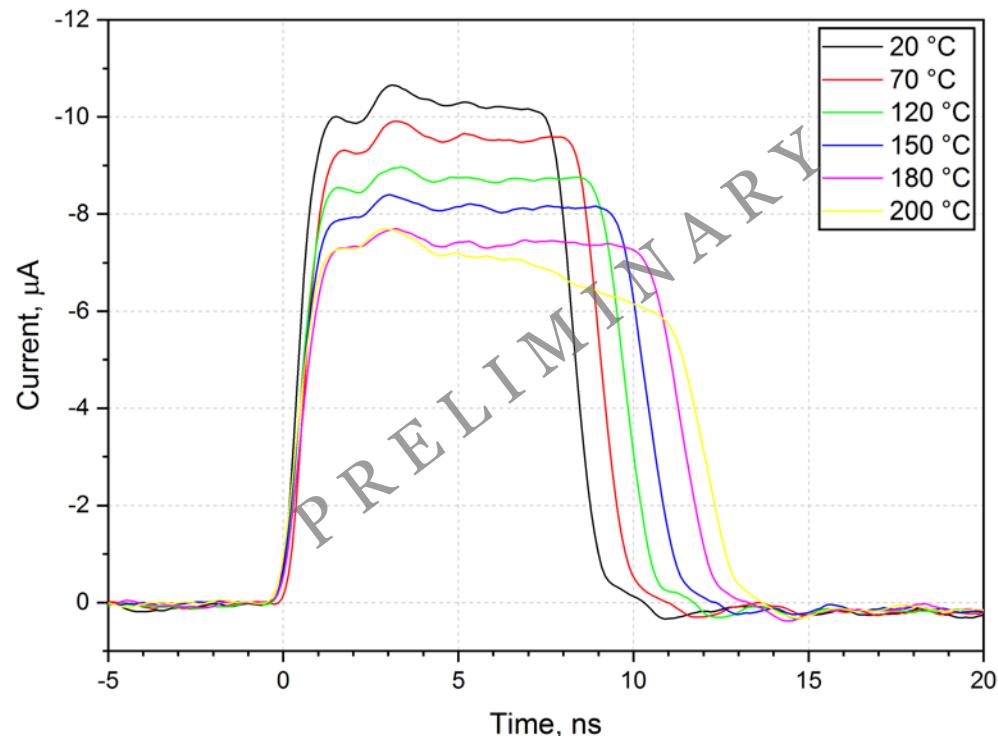


Pos. HV Bias
(ca. 1 V/ μm)



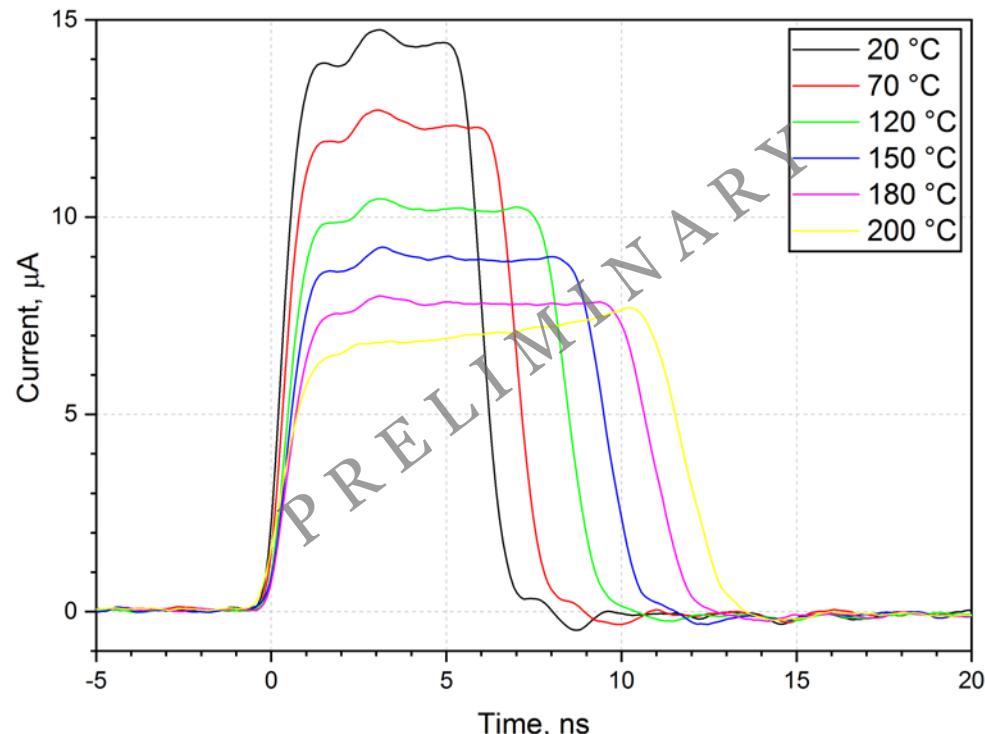
Preliminary Results – TCT

- 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

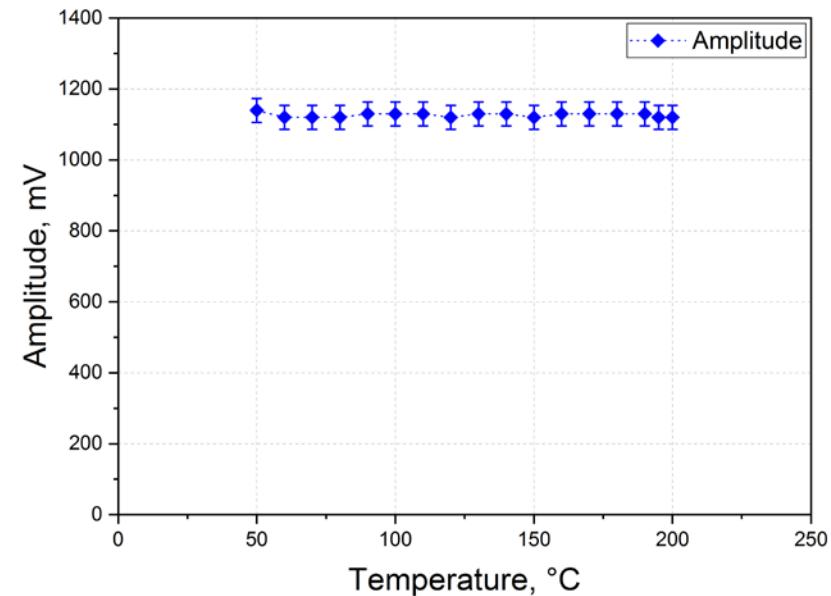
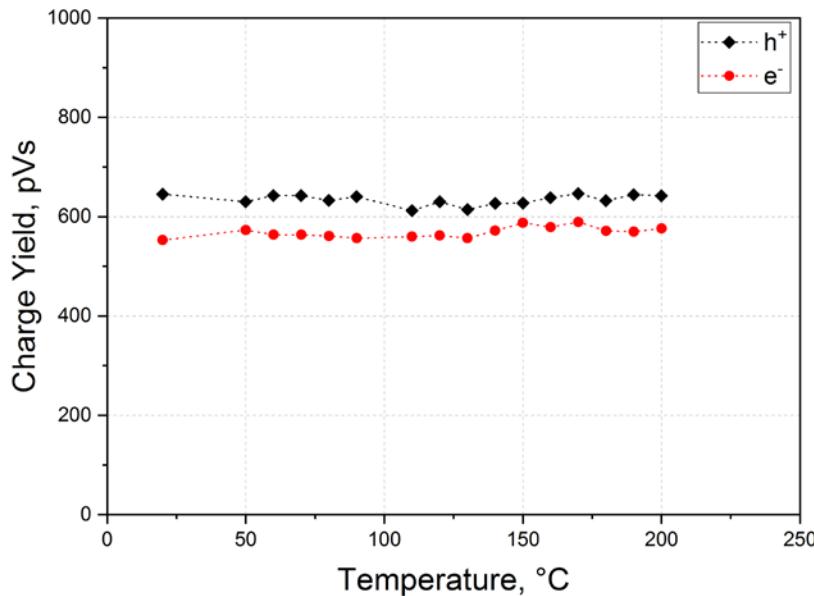


Preliminary Results – TCT

- 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
- Electron holes:
 - signal form similar to electrons
 - a bit higher and faster

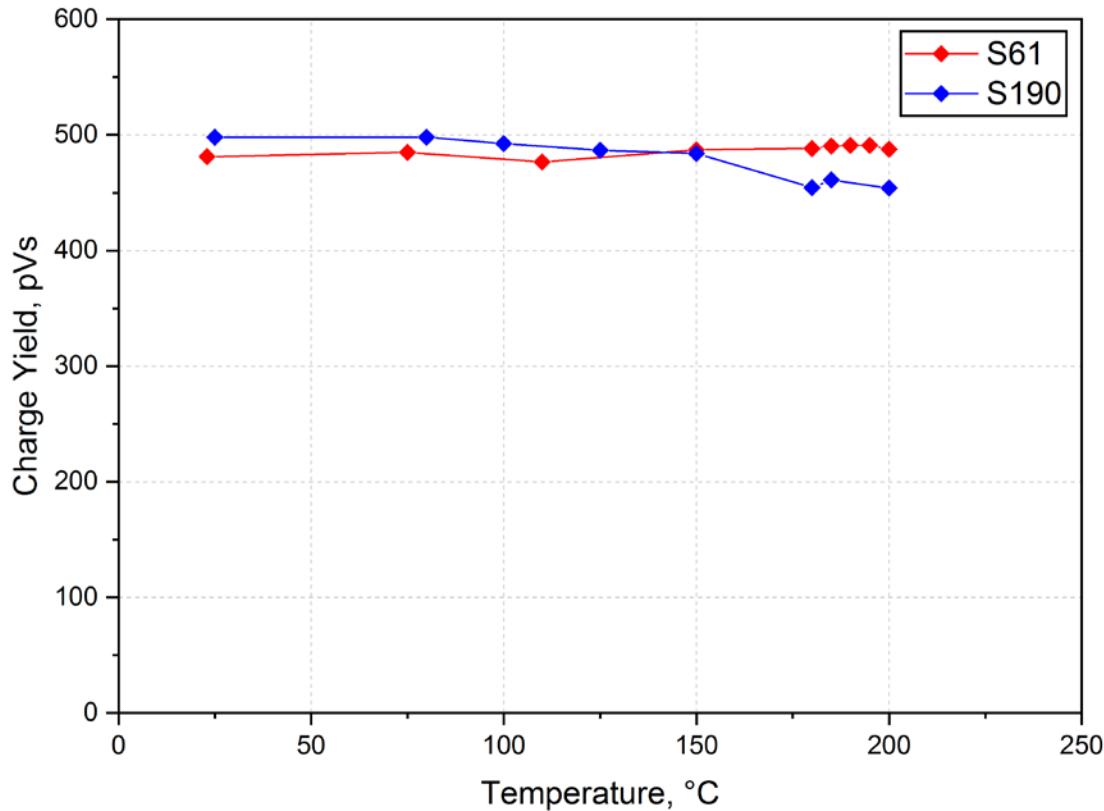


Preliminary Results – Charge Yields & Amplitude



- 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

- 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 separator detector array (e.g. COLD)

High-Temperature α -Spectroscopy

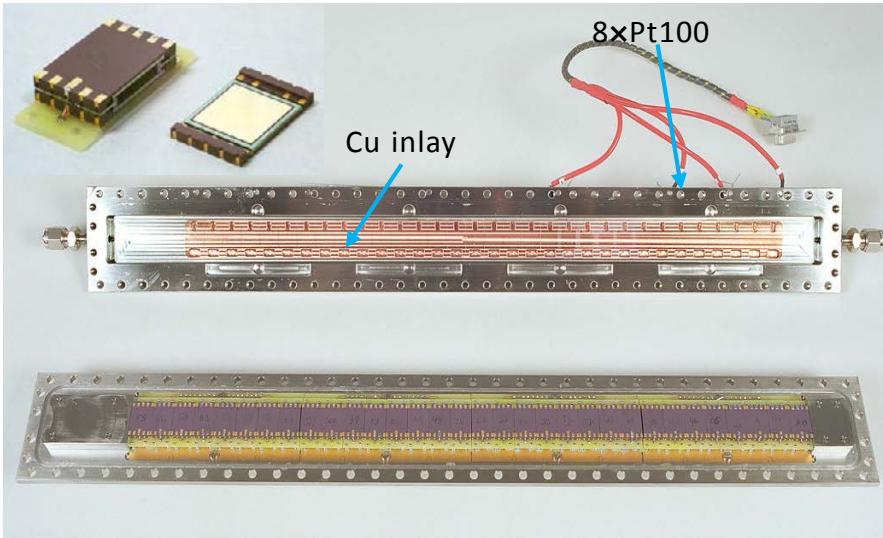
- For online measurement of TANs in IVAC:
 - Detector needed to work in vicinity of high temperature and strong IR/vis/UV-radiation

- 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)

- For TAN chemistry: thermochromatographic separator detector arrays
 - PSI: **Cryo On-Line Detector (COLD)**
 - GSI: **Cryo-Online-Multidetector for Physics And Chemistry of Transactinides (COMPACT)**
 - LBNL: **Cryo-Thermochromatographic Seperator (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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