Chemie radioaktivních prvků

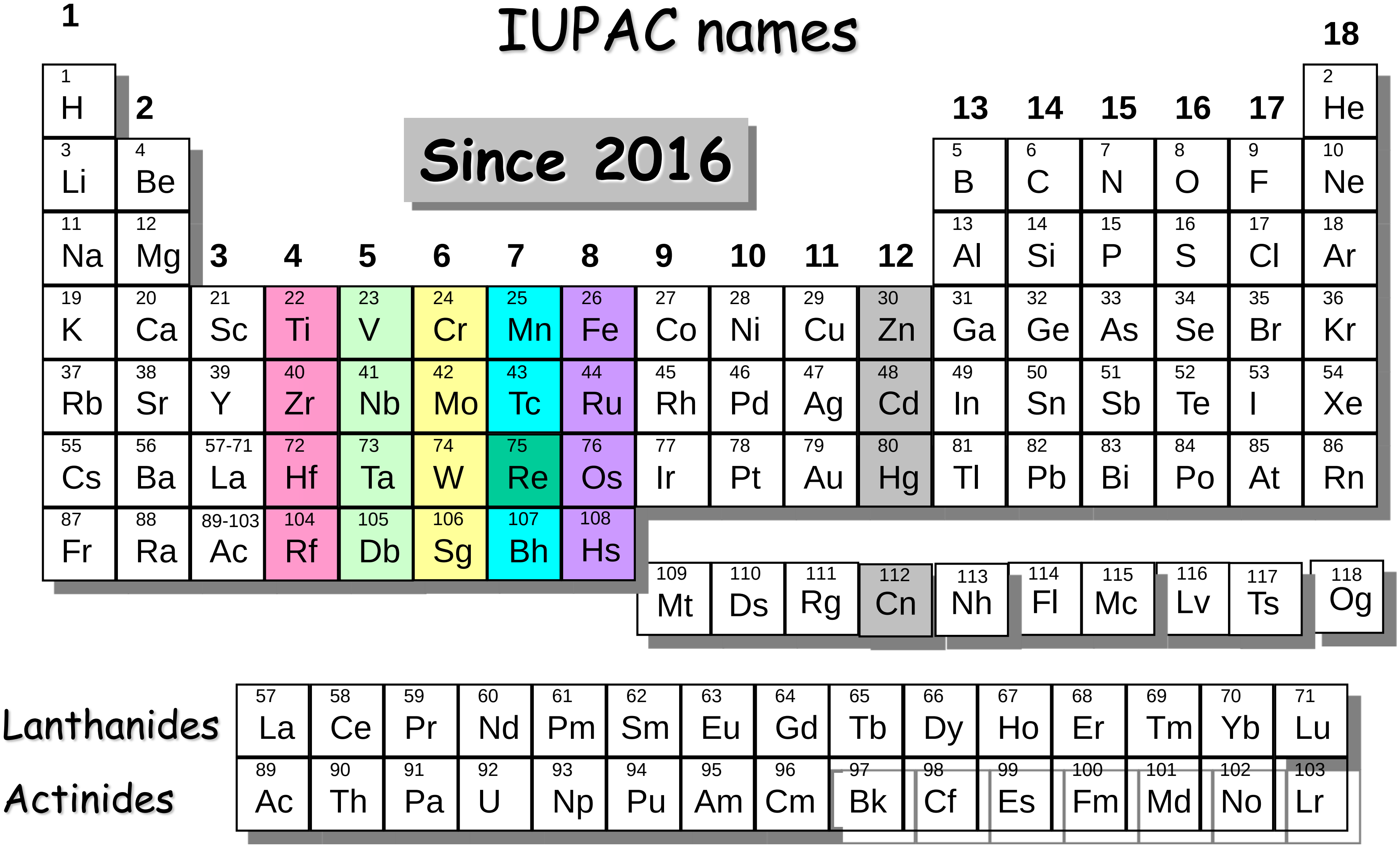
část 3 - transaktinoidy

J. John

Periodic table of the elements

IUPAC names

Since 2016



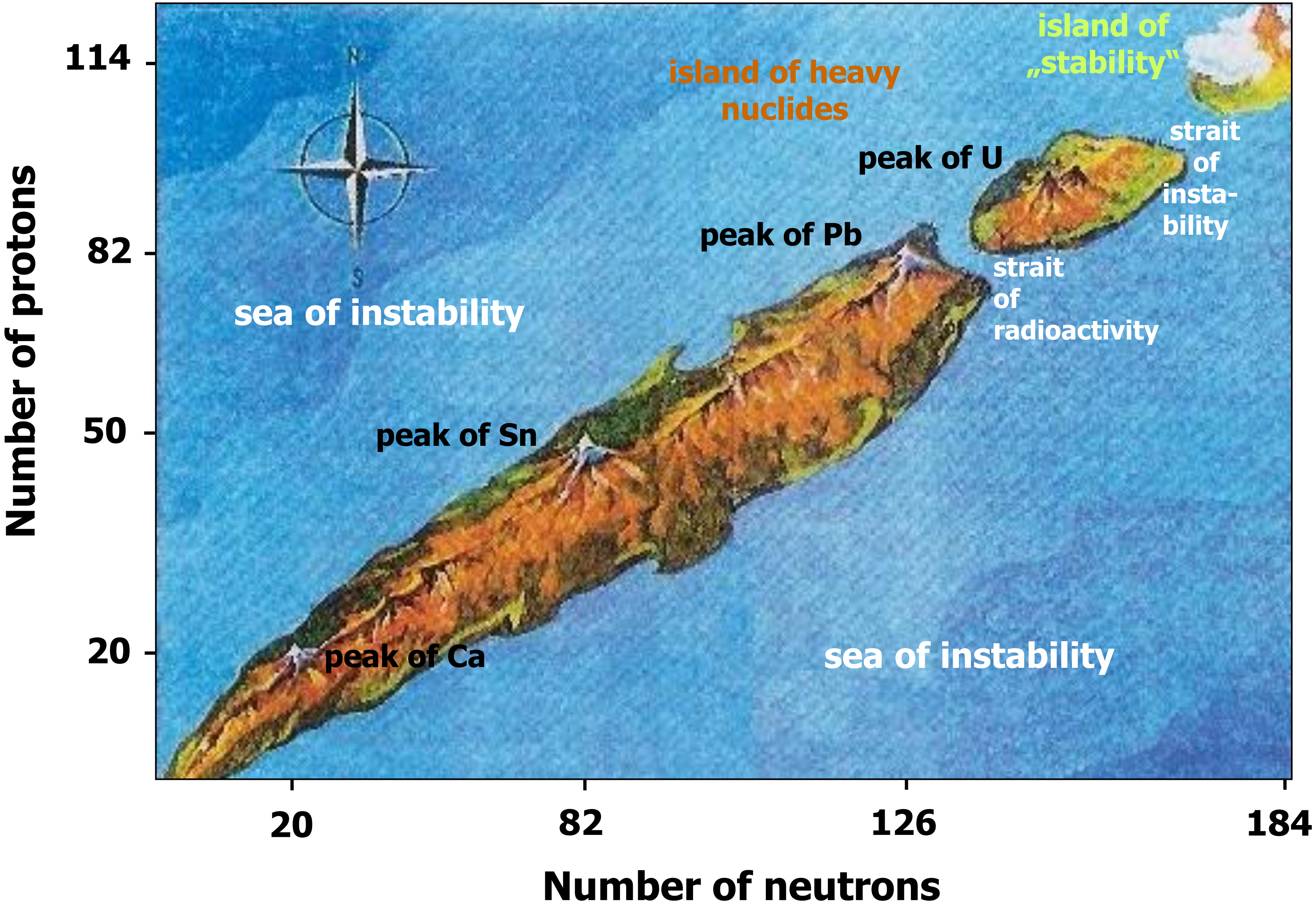
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Superheavy Elemens - Why Study?

- Test validity of the Extrapolations of the Periodic Table
- Determine the Influence of Relativistic Effects on Chemical Properties
- Help to Predict the Chemical Properties of the Heavier Elements
- Determine Nuclear Properties of the Heaviest Elements

Superheavy Elemens - Stability?



SHE - produktion

Hot fusion – light projectile on heavy target, e.g.

$^{248}\mathrm{Cm} + {}^{22}\mathrm{Na} \rightarrow {}^{266}\mathrm{Sg} + 4\mathrm{n}$

Compound nucleus, in this case $^{270}\mathrm{Sg}$, is highly excited and a certain number of neutrons ”evaporates”. Each of these neutrons takes with it some 10 MeV of energy.

Cold fusion – medium weight projectile on lighter target, e.g.

$^{208}\mathrm{Pb} + {}^{50}\mathrm{Ti} \rightarrow {}^{257}\mathrm{Rf} + \mathrm{n}$

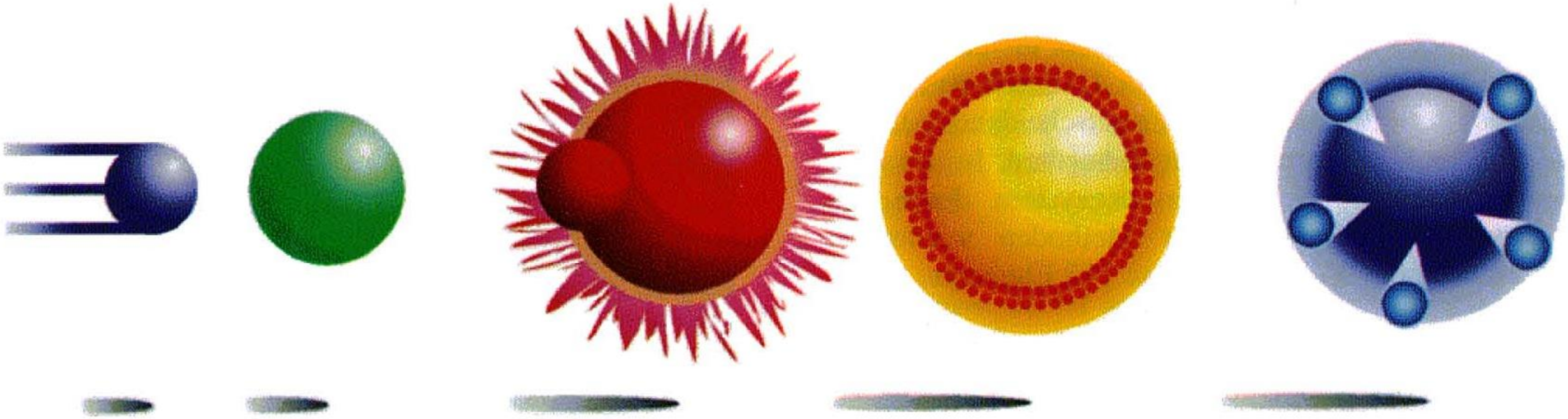
In this case is the compound nuclues not so highly excited and only 0-1 neutrons ”evaporate”.

Accelerators – Dubna, Darmstadt, Berkeley and RIKEN

Hot fusion with $^{48}\mathrm{Ca}$ ions as projectile allowed to reach the ”island of stability” around $Z = 114$ and $N = 182$. ($N/Z = 1.6$)

Synthesis of heavy elements: Hassium (*Z*=108)

$^{248}\mathrm{Cm}(^{26}\mathrm{Mg}, 5n)^{269}\mathrm{Hs}$



$^{26}\mathrm{Mg}$ $^{248}\mathrm{Cm}$ FUSION $^{274}\mathrm{Hs}^{*}$ $^{269}\mathrm{Hs}$

1×10^{17} 2×10^{18} 5×10^{8} 1

projectiles on target compound nuclei atom

Superheavy Elemens - Current Status

Atomic number	Name	Chemical symbol
104	**rutherfordium**	**Rf**
105	**dubnium**	**Db**
106	**seaborgium**	**Sg**
107	**bohrium**	**Bh**
108	**hassium**	**Hs**
109	**meitnerium**	**Mt**
110	**darmstadtium**	**Ds**
111	**roentgenium**	**Rg**
112	**copernicium**	**Cn**
113	**nihonium**	**Nh**
114	**flerovium**	**Fl**
115	**moscovium**	**Mc**
116	**livermorium**	**Lv**
117	**tenessin**	**Ts**
118	**oganesson**	**Og**

104 – Rutherfordium (Rf)

1964: Dubna (Russia), Flerov et al.

$^{242}Pu(^{22}Ne,4n)^{260}104 \xrightarrow{SF,\,0.3\,s}$ **Kurchatovium (Ku)**

$\sigma \approx 0.2$ nb 1 at/5 hr

1969: Berkeley (USA), Ghiorso et al.

$^{249}Cf(^{12,13}C,4n)^{257,259}104 \xrightarrow{\alpha}$ **Rutherfordium (Rf)**

Final determination of Z for $^{257}104$ – coicidence of K_X of No with α from $^{257}104$

Today: A = 253-262

$^{261}104$ $T_{1/2} = 1.1$ min α $^{248}Cm(^{18}O,5n)$

Chemistry

Eka-hafnium.

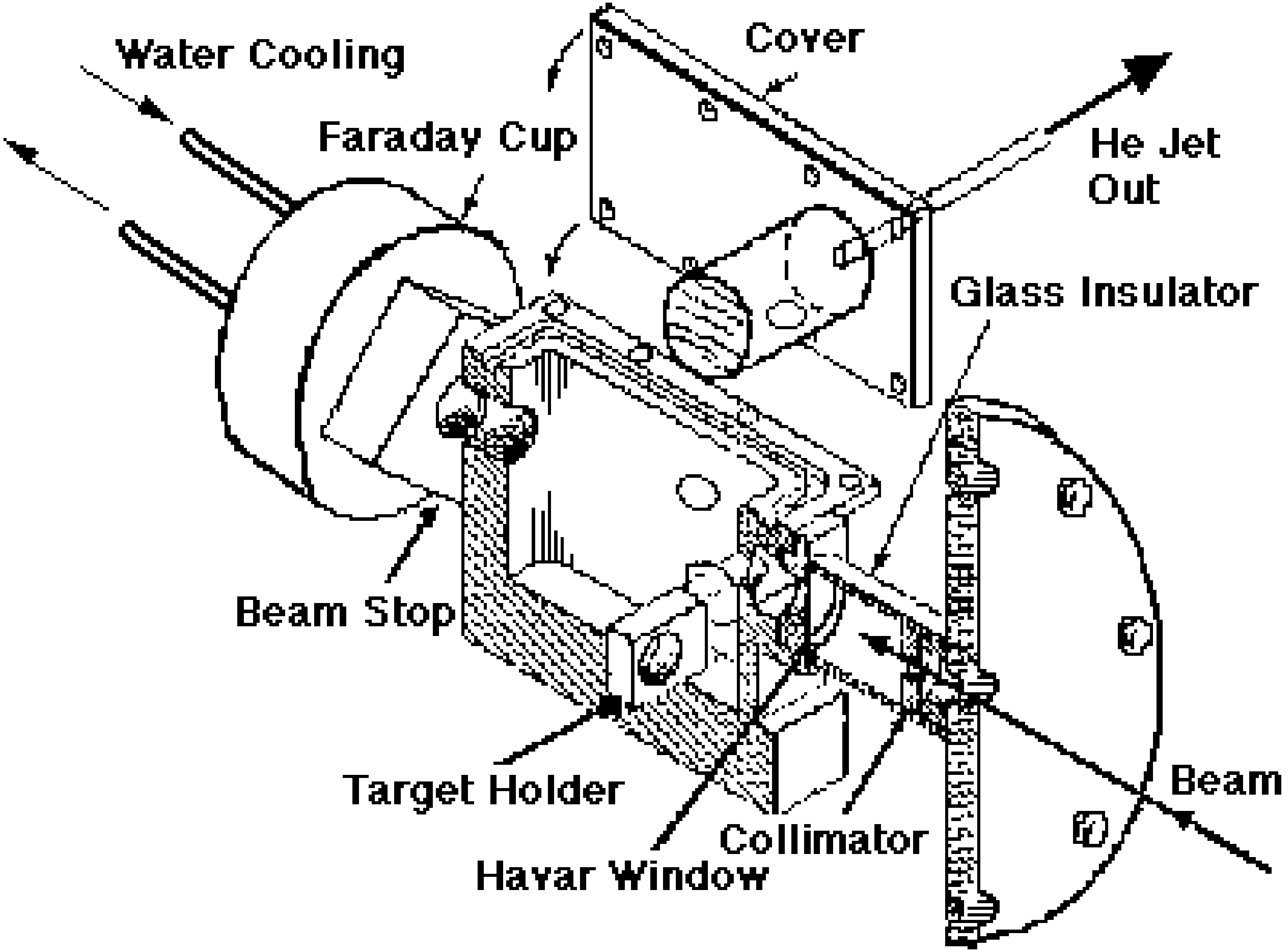
Dubna – volatile chloride (Zvára et al., 1966) (?)

Berkeley & Oak Ridge (Silva, 1970):

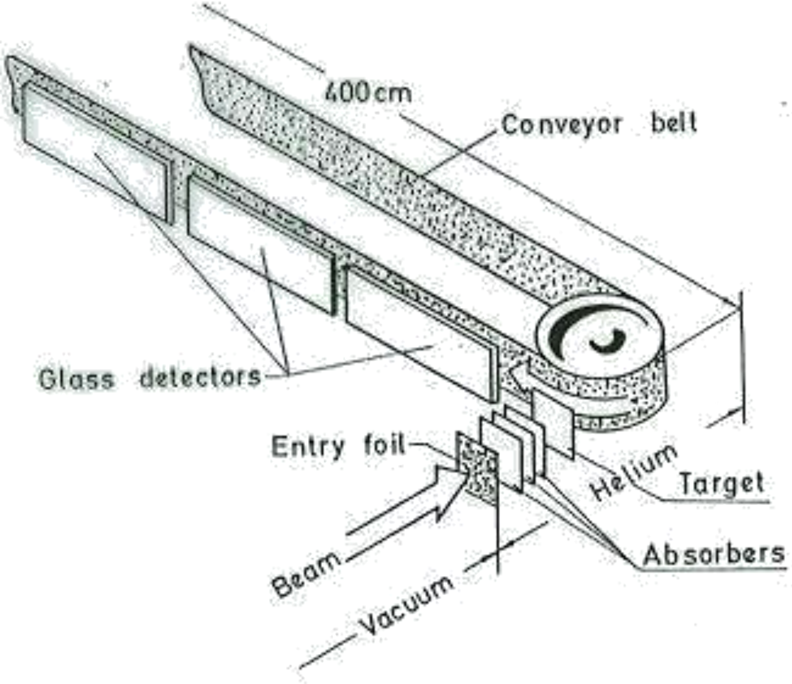
Dowex 50 + α-HiB – behaves like IV, **NOT** III

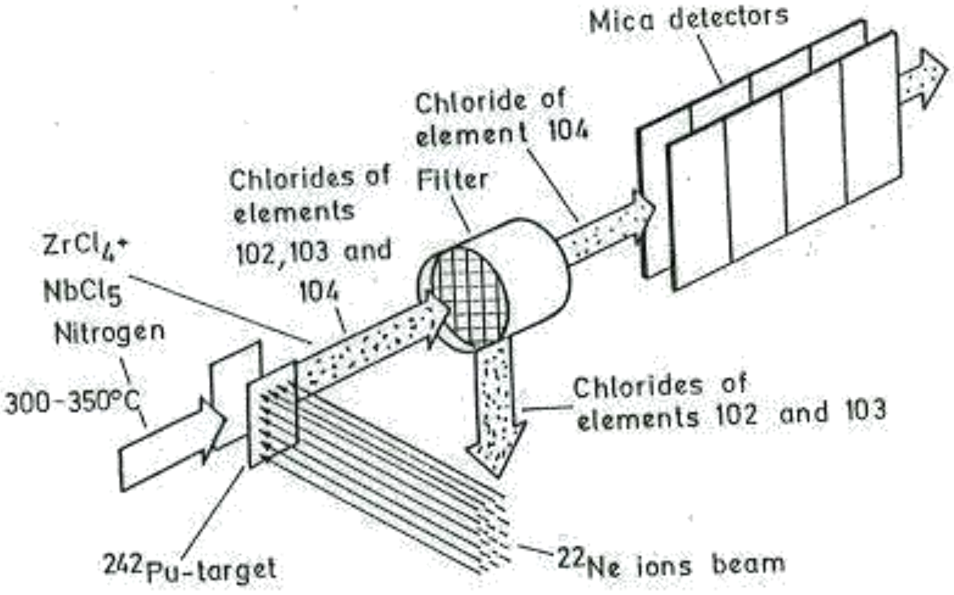
study performed with 100 atoms of ^{261}Rf

SHE – Rf: Target System

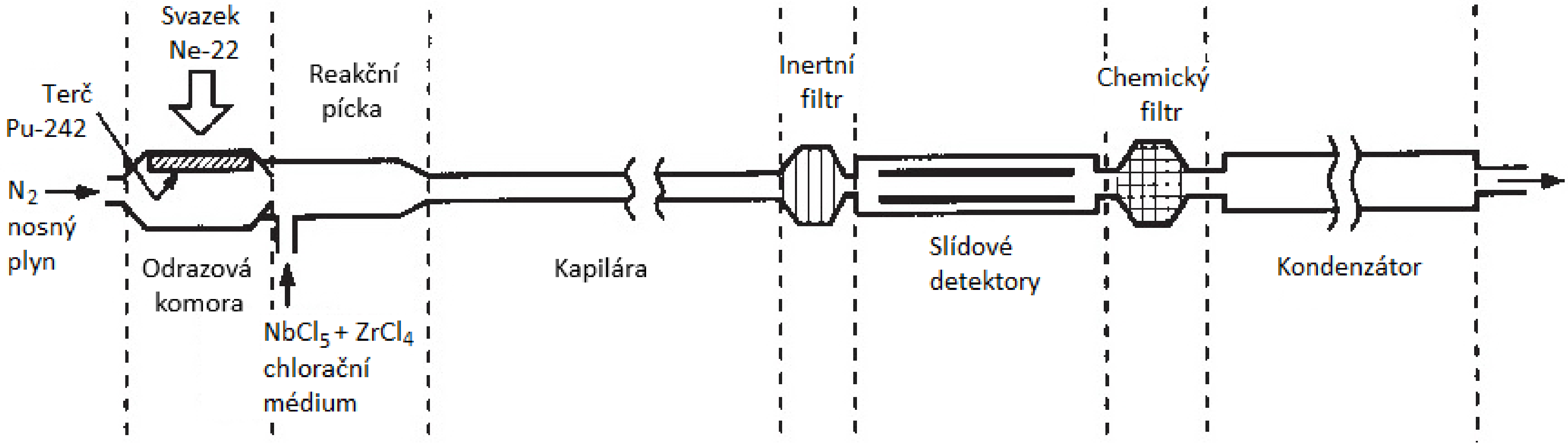


^{104}Rf


400cm
Conveyor belt
Glass detectors
Entry foil
Helium
Target
Absorbers
Beam
Vacuum


Mica detectors
Chloride of element 104
Filter
Chlorides of elements 102, 103 and 104
ZrCl4+
NbCl5
Nitrogen
300-350°C
Chlorides of elements 102 and 103
242Pu-target
22Ne ions beam

^{104}Rf


Svazek
Ne-22
Terč
Pu-242
Reakční
pícka
Inertní
filtr
Chemický
filtr
N_2
nosný
plyn
Odrazová
komora
Kapilára
Slídové
detektory
Kondenzátor
$NbCl_5 + ZrCl_4$
chlorační
médium

105 – Dubnium (Db)

1968: Dubna (Russia), Flerov et al.

$\mathbf{^{243}Am(^{22}Ne,4n)^{261}105 \xrightarrow{\alpha,\ 0,1-0.3\ s} {}^{257}Lr}$ $\mathbf{E_{\alpha} = 9.4\ MeV}$

$\mathbf{^{243}Am(^{22}Ne,5n)^{260}105 \xrightarrow{\alpha,\ 0.01\ s} {}^{256}Lr}$ $\mathbf{E_{\alpha} = 9.7\ MeV}$

⇒ Nielsbohrium (Ns)

1970: Berkeley (USA), Ghiorso et al.

$\mathbf{^{249}Cf(^{15}N,5n)^{260}105 \xrightarrow{\alpha,\ 1.6\ s} {}^{256}Lr \longrightarrow}$

“Proof“ – coincidence 105 - Lr

⇒ Hahnium (Ha)

Final determination of Z (1977) – coincidence of L_X of Lr with α from $^{260}105$

Today: A = 255-262

^{262}Db $T_{1/2} = 34$ s 78 % SF, 22 % α $^{249}Bk(^{18}O,5n)$

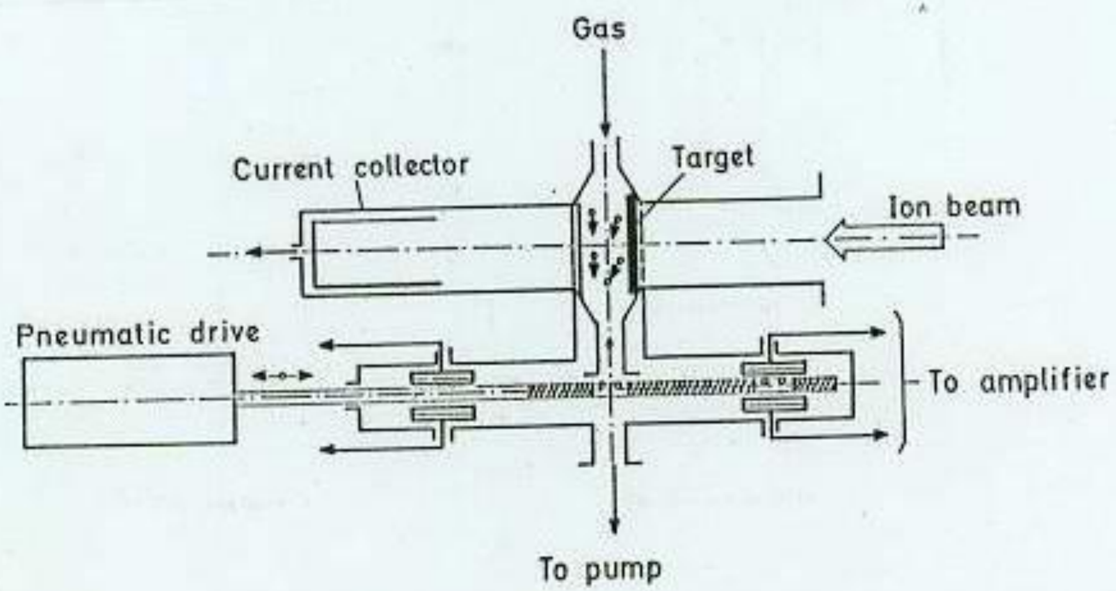
Chemistry

Dubna – gas chromatography $T \in <50; 350>$ °C

Volatilily of chlorides: $\mathbf{HfCl_4 < DbCl_x < NbCl_5} \Rightarrow$

Eka-tantalum (Zvára et al., 1970-75)

105


Gas
Current collector
Target
Ion beam
Pneumatic drive
To amplifier
To pump

106 – Seaborgium (Sg)

Forecast: Eka-tungsten
1974: Berkeley (USA), Ghiorso et al.

$^{249}\mathrm{Cf}(^{18}\mathrm{O},4\mathrm{n})^{263}106 \xrightarrow{\alpha,\,0.9\,s}$ $E_{\alpha} = 9.06\ \mathrm{MeV}$

“Proof“ – correlation of decays $^{263}106 \rightarrow {}^{259}\mathrm{Rf} \rightarrow {}^{255}\mathrm{No}$

1974: Dubna (Russia), Oganesyan et al.

$^{207,208}\mathrm{Pb}(^{54}\mathrm{Cr},2\text{-}3\mathrm{n})^{259}106 \xrightarrow{SF,\,?\,ms}$

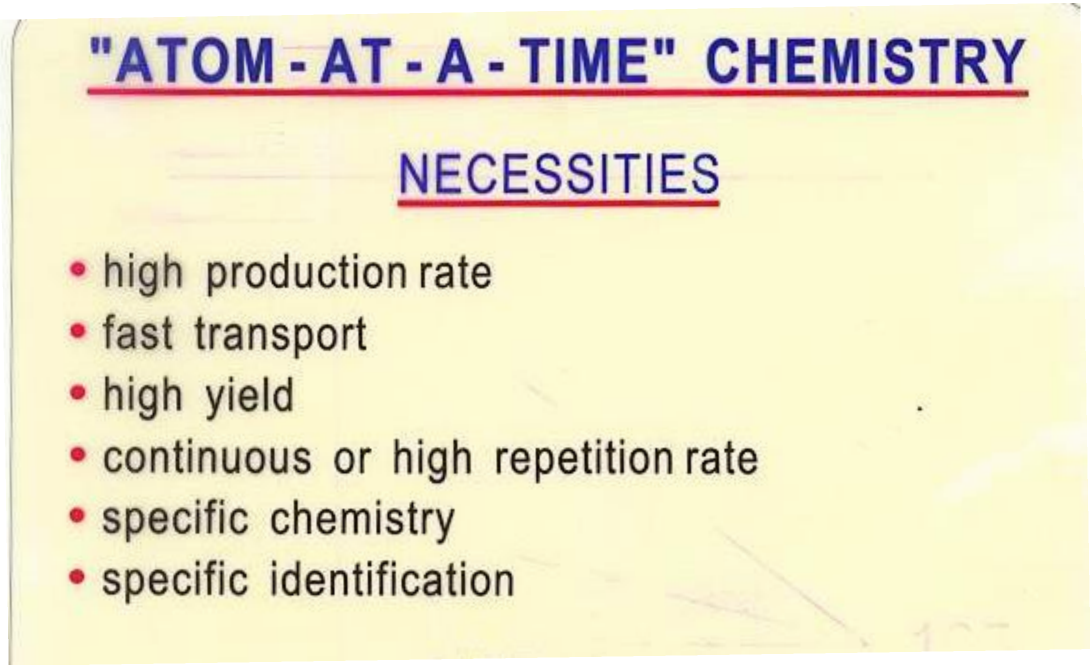
(probably $^{260}106 \xrightarrow{\alpha}$ $^{256}\mathrm{Rf} \xrightarrow{SF}$)

Today: A = 259-263
$^{263}\mathrm{Sg}$ $T_{1/2} = 0.9$ s α $^{249}\mathrm{Cf}(^{18}\mathrm{O},4\mathrm{n})$

Chemistry
Theoretical forecast: like W or Mo, more complexes
Experimental: **Atom – at – a - time chemistry**
⇒ **member of group 6 of the PTE**

Jména prvků se Z = 102–109 navrhovaná v letech 1992 až 1997

Z	GSI 1992	ACS 1994	IUPAC 1994	IUPAC 1995	IUPAC 1997
102	joliotium	nobelium	nobelium	flerovium	nobelium, No
103	lawrencium	lawrencium	lawrencium	lawrencium	lawrencium, Lr
104	meitnerium	rutherfordium	dubnium	dubnium	rutherfordium, Rf
105	kurchatovium	hahnium	joliotium	joliotium	dubnium, Db
106	rutherfordium	seaborgium	rutherfordium	seaborgium	seaborgium, Sg
107	nielsbohrium	nielsbohrium	bohrium	nielsbohrium	bohrium, Bh
108	hassium	hassium	hahnium	hahnium	hassium, Hs
109	hahnium	meitnerium	meitnerium	meitnerium	meitnerium, Mt

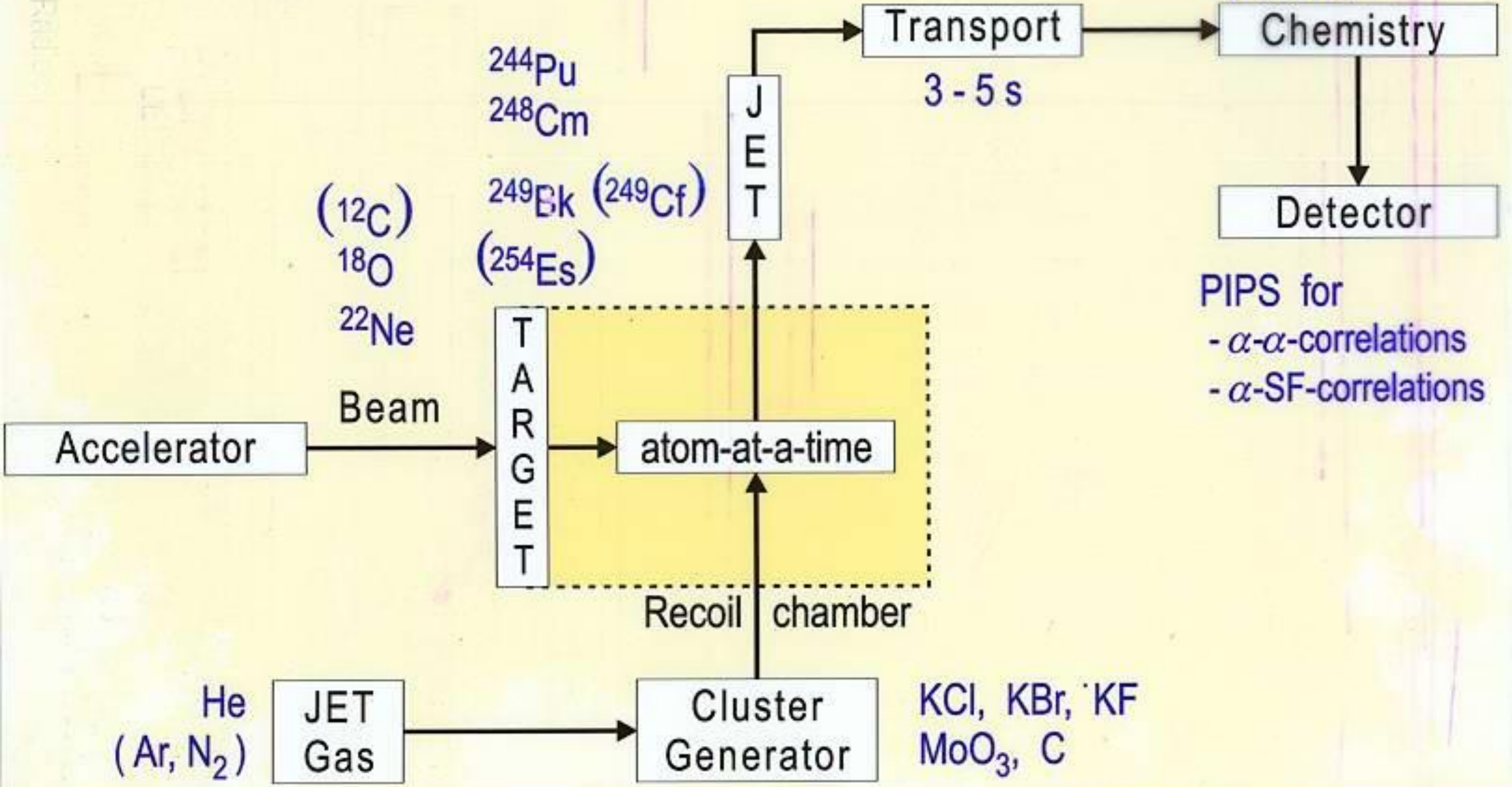


"ATOM - AT - A - TIME" CHEMISTRY

NECESSITIES

- high production rate
- fast transport
- high yield
- continuous or high repetition rate
- specific chemistry
- specific identification

EXPERIMENT SCHEME



Gas chemistry:
- OLGA

Aqueous chemistry:
- ARCA

(- SISAK)

Transport

3 - 5 s

Chemistry

Detector

PIPS for
- α-α-correlations
- α-SF-correlations

^{244}Pu

^{248}Cm

^{249}Bk (^{249}Cf)

(^{254}Es)

(^{12}C)

^{18}O

^{22}Ne

JET

Accelerator

Beam

TARGET

atom-at-a-time

Recoil chamber

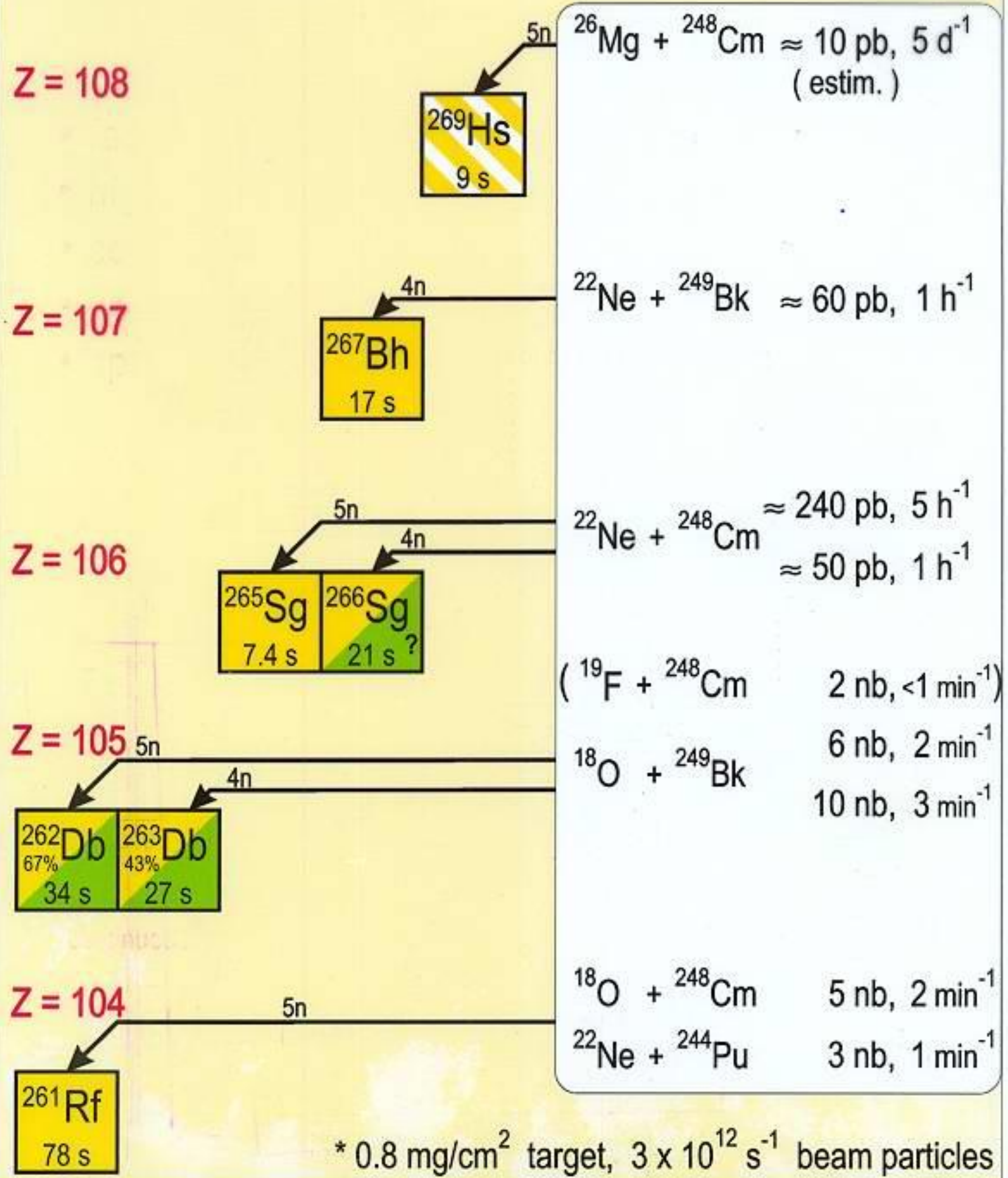
He
(Ar, N_2)

JET Gas

Cluster Generator

KCl, KBr, KF
MoO_3, C

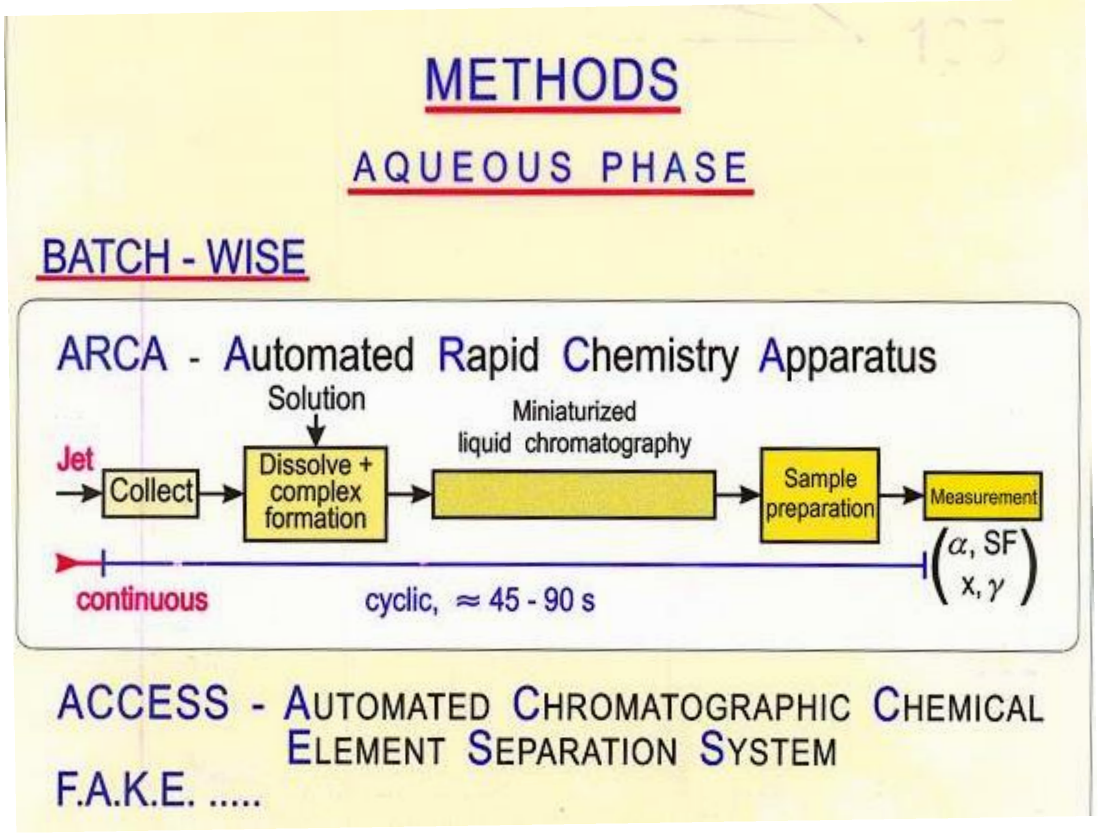
NUCLEAR SYNTHESES



reaction	cross section,	production rate*
$^{26}Mg + {}^{248}Cm$	≈ 10 pb, (estim.)	$5\ d^{-1}$
$^{22}Ne + {}^{249}Bk$	≈ 60 pb,	$1\ h^{-1}$
$^{22}Ne + {}^{248}Cm$	≈ 240 pb, ≈ 50 pb,	$5\ h^{-1}$ $1\ h^{-1}$
($^{19}F + {}^{248}Cm$	2 nb,	$<1\ min^{-1}$)
$^{18}O + {}^{249}Bk$	6 nb, 10 nb,	$2\ min^{-1}$ $3\ min^{-1}$
$^{18}O + {}^{248}Cm$	5 nb,	$2\ min^{-1}$
$^{22}Ne + {}^{244}Pu$	3 nb,	$1\ min^{-1}$

* 0.8 mg/cm^2 target, $3 \times 10^{12}\ s^{-1}$ beam particles

Aqueous chemistry with Transactinides



METHODS

AQUEOUS PHASE

BATCH - WISE

ARCA - Automated Rapid Chemistry Apparatus

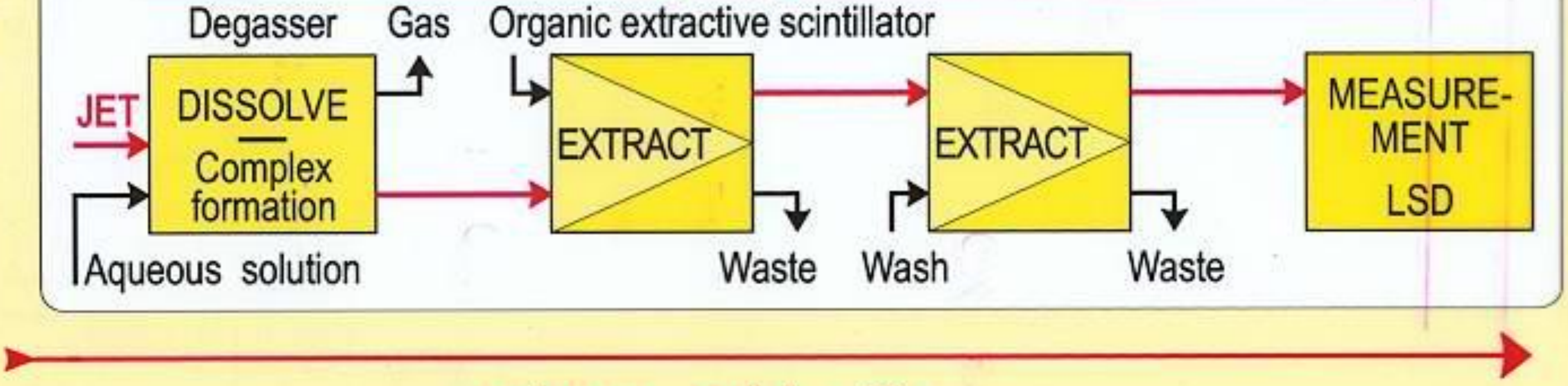
ACCESS - Automated Chromatographic Chemical Element Separation System

F.A.K.E. .....

Continuous Separation and Detection

SISAK III $3\ \mathrm{s} \leq T_{1/2} \leq 30\ \mathrm{s}$

SISAK - fast centrifuge system for solvent extraction



Degasser

Gas

Organic extractive scintillator

JET

DISSOLVE — Complex formation

EXTRACT

EXTRACT

MEASUREMENT LSD

Aqueous solution

Waste

Wash

Waste

continuous, ≈ 0.1 - 10 s

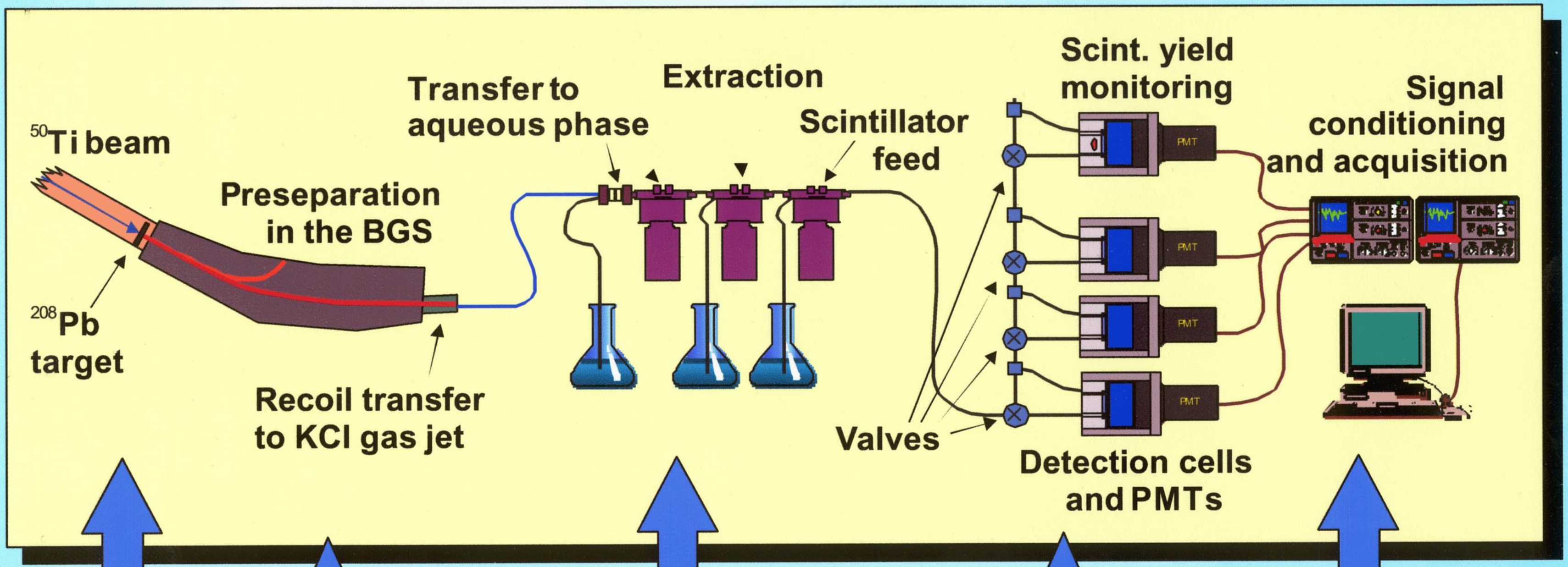
Oslo - Göteborg - Mainz - Collaboration

H. Persson et al., Radiochim. Acta 48 (1989) 177

J. Alstad et al., JRNC 189 (1995) 133

B. Wierczinski et al., NIM A 370 (1996) 532

Overview



Production

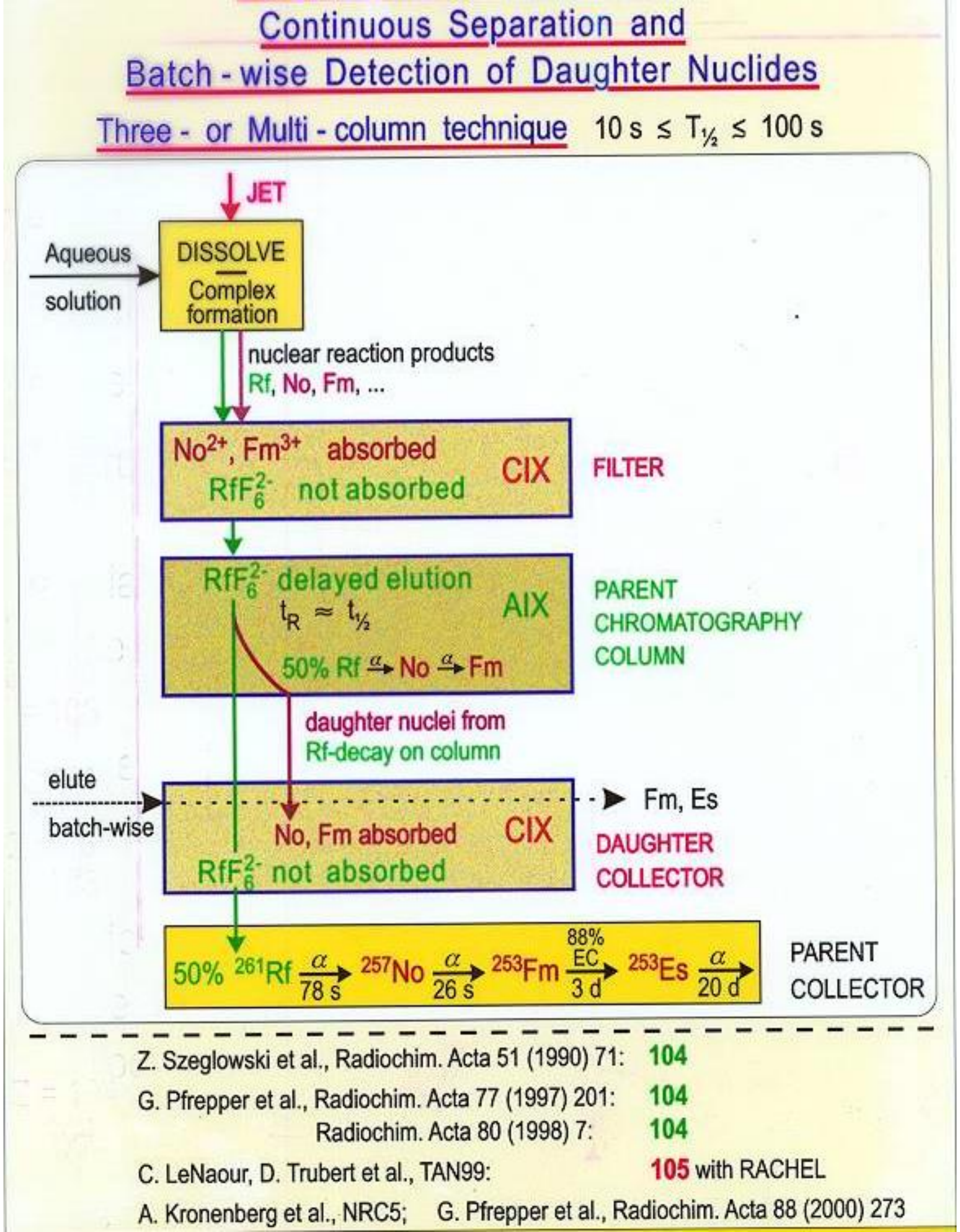
Separation

Chemical experiment

Detection

Data acquisition

Rf



Continuous Separation and Batch - wise Detection of Daughter Nuclides

Three - or Multi - column technique $10\ s \leq T_{1/2} \leq 100\ s$

JET

Aqueous solution

DISSOLVE
Complex formation

nuclear reaction products
Rf, No, Fm, ...

No^{2+}, Fm^{3+} absorbed
RfF_6^{2-} not absorbed
CIX

FILTER

RfF_6^{2-} delayed elution
$t_R \approx t_{1/2}$
50% $Rf \xrightarrow{\alpha} No \xrightarrow{\alpha} Fm$
AIX

PARENT
CHROMATOGRAPHY
COLUMN

daughter nuclei from
Rf-decay on column

elute
batch-wise

No, Fm absorbed
RfF_6^{2-} not absorbed
CIX

Fm, Es

DAUGHTER
COLLECTOR

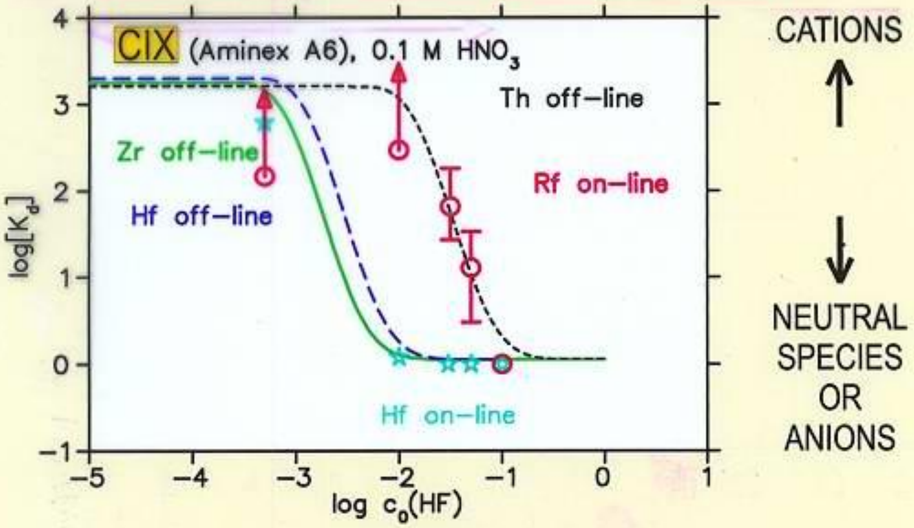
$50\%\ {}^{261}Rf \xrightarrow[78\ s]{\alpha} {}^{257}No \xrightarrow[26\ s]{\alpha} {}^{253}Fm \xrightarrow[3\ d]{88\%\ EC} {}^{253}Es \xrightarrow[20\ d]{\alpha}$

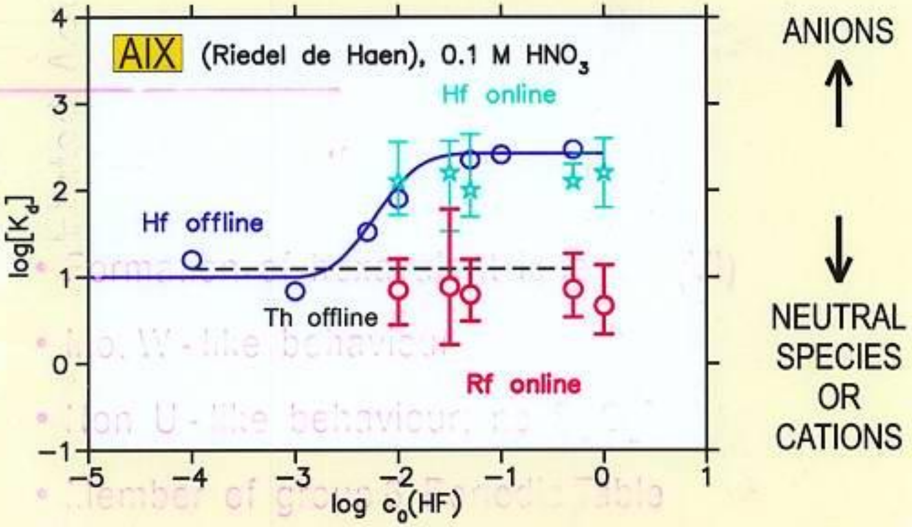
PARENT
COLLECTOR

Z. Szeglowski et al., Radiochim. Acta 51 (1990) 71: **104**
G. Pfrepper et al., Radiochim. Acta 77 (1997) 201: **104**
Radiochim. Acta 80 (1998) 7: **104**
C. LeNaour, D. Trubert et al., TAN99: **105** with RACHEL
A. Kronenberg et al., NRC5; G. Pfrepper et al., Radiochim. Acta 88 (2000) 273

Th - LIKE BEHAVIOUR OF $_{104}$Rf

ARCA - 0.1 M HNO_3, var. conc. HF



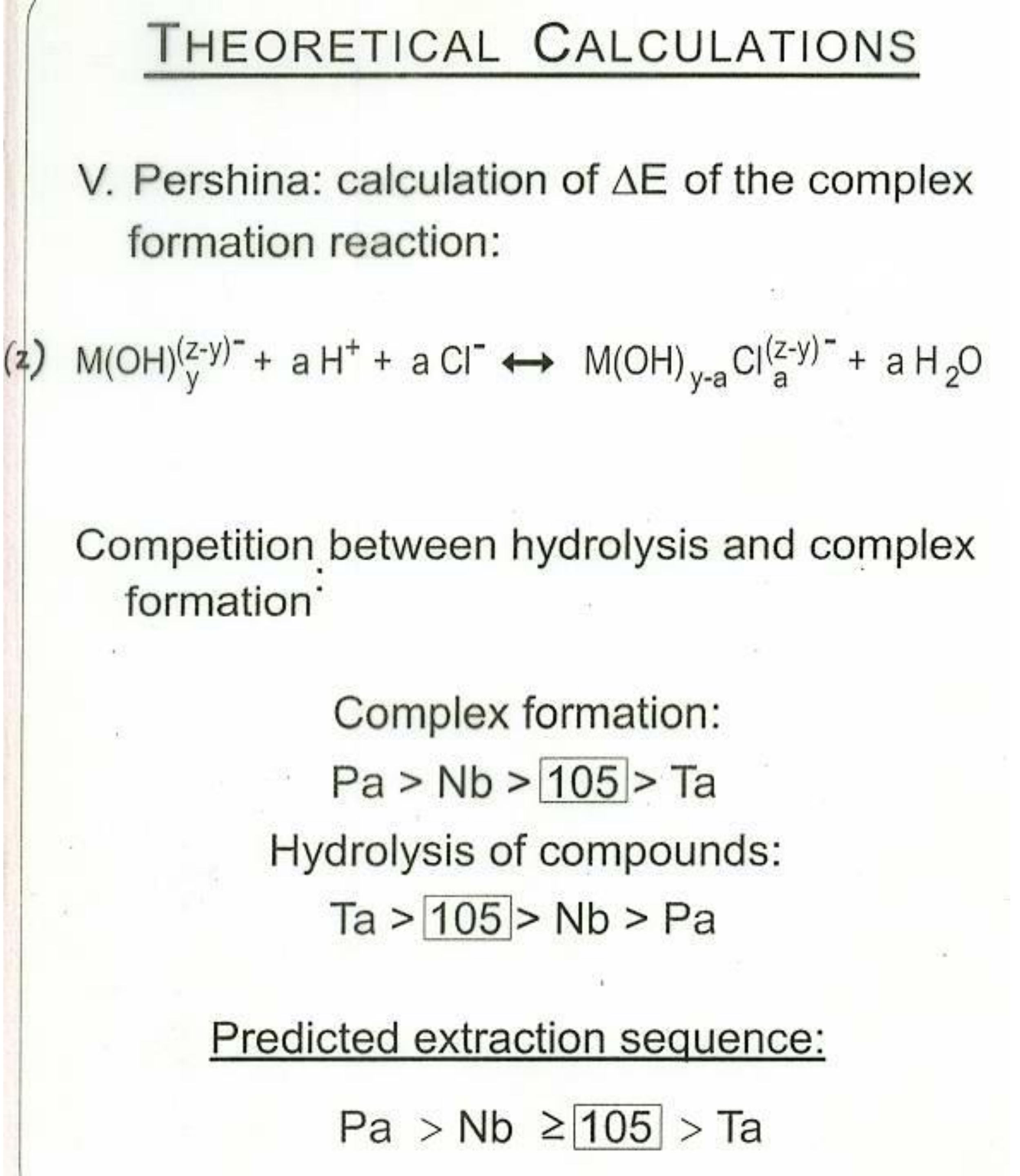


F^- - COMPLEX FORMATION

$\boxed{\text{Zr} \geq \text{Hf} \gg {}_{104}\text{Rf} \approx \text{Th}}$

E. Strub et al., Radiochim. Acta 88 (2000) 265

Db



THEORETICAL CALCULATIONS

V. Pershina: calculation of ΔE of the complex formation reaction:

(2) $$M(OH)_y^{(z-y)-} + a\,H^+ + a\,Cl^- \longleftrightarrow M(OH)_{y-a}Cl_a^{(z-y)-} + a\,H_2O$$

Competition between hydrolysis and complex formation

Complex formation:

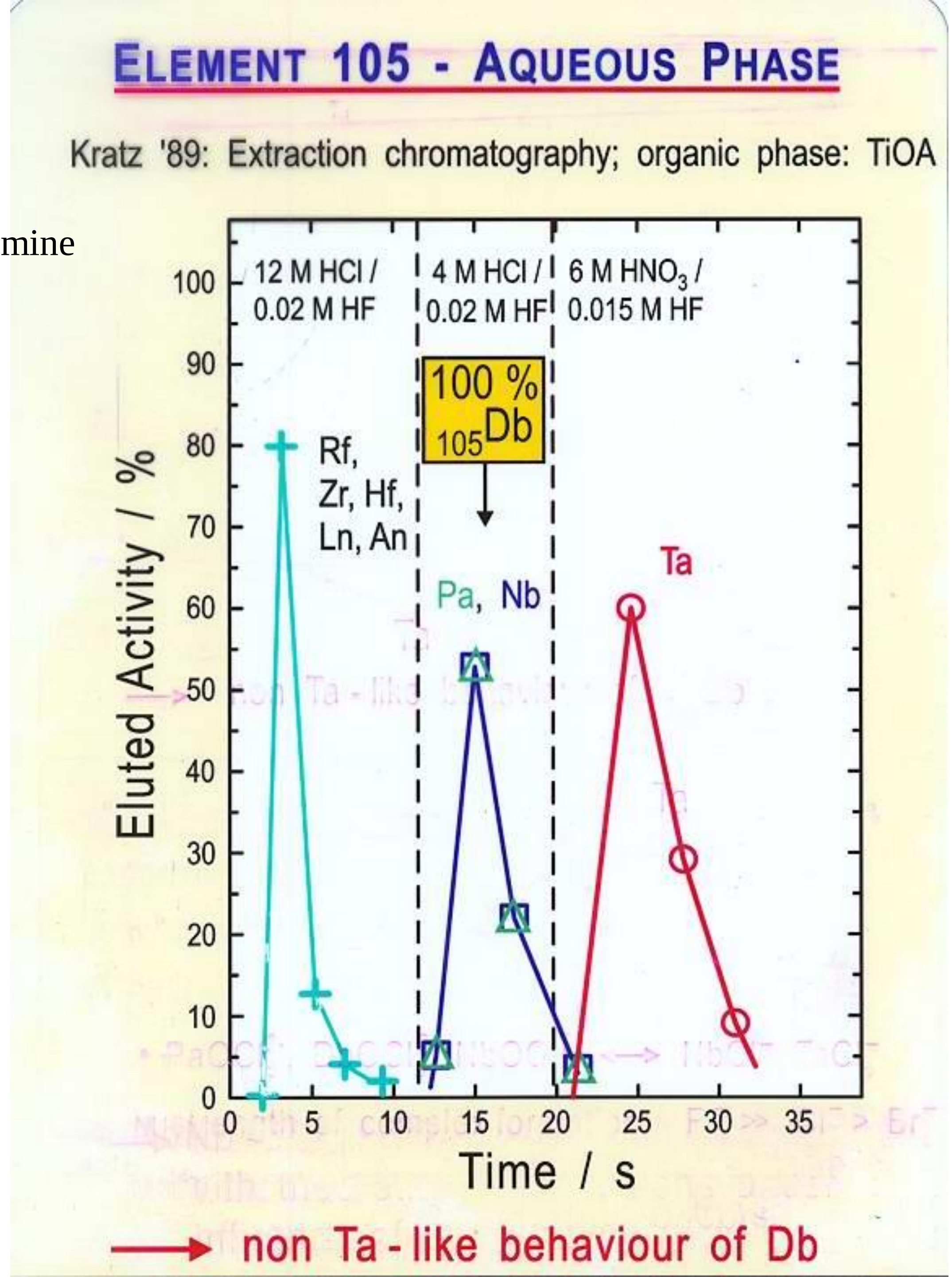
$Pa > Nb > \boxed{105} > Ta$

Hydrolysis of compounds:

$Ta > \boxed{105} > Nb > Pa$

Predicted extraction sequence:

$Pa > Nb \geq \boxed{105} > Ta$



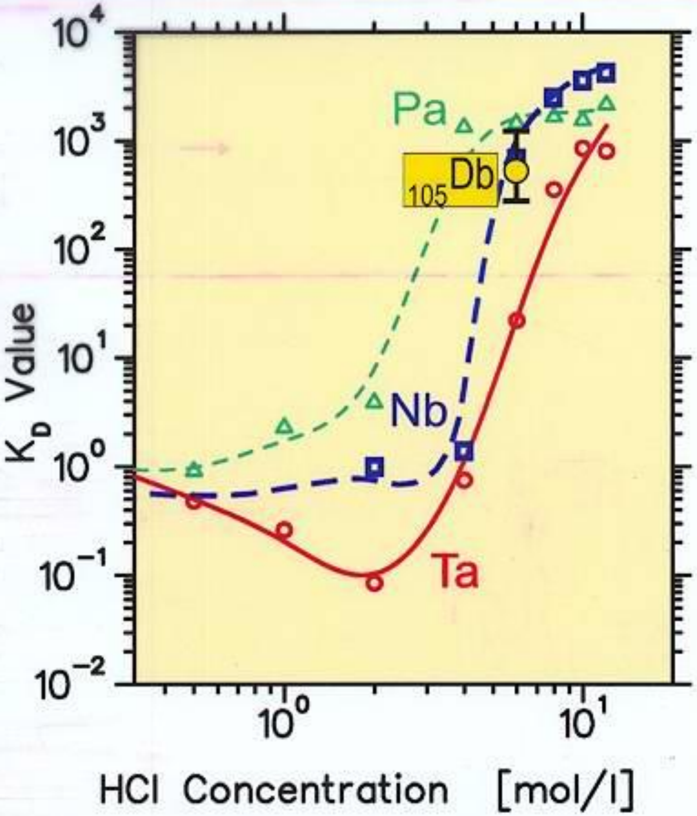
ELEMENT 105 - AQUEOUS PHASE

Kratz '89: Extraction chromatography; organic phase: TiOA

→ non Ta - like behaviour of Db

TiOA = tri-iso-octyl amine
Diluent: toluene

$_{105}$Db BEHAVIOUR IN THE SYSTEM ALIQUAT 336 / HCl (without HF !)



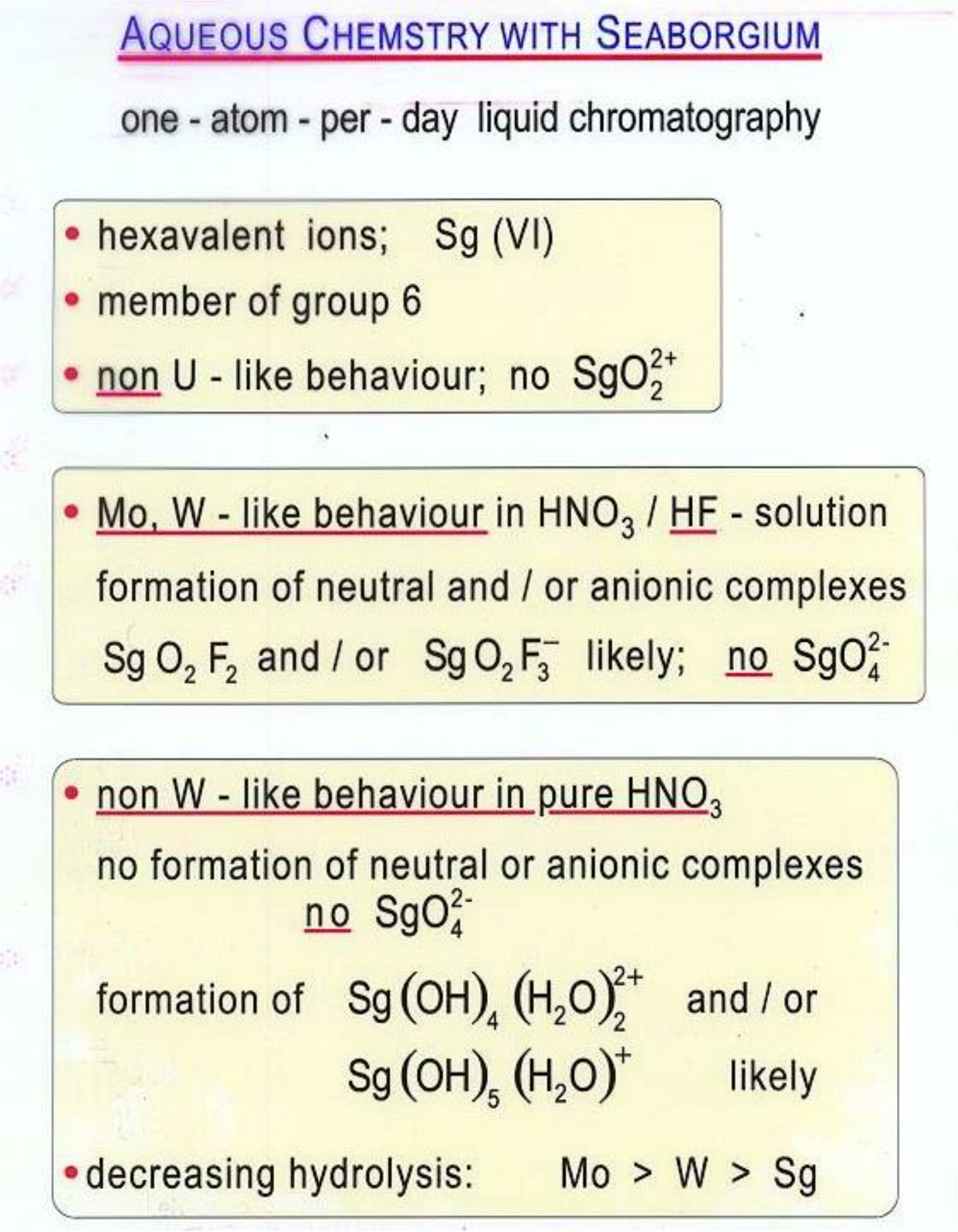
K_D - values (6 M HCl)

Pa > Nb ≳ $_{105}$Db > Ta

$1440 > 683 \gtrsim \left(438^{+532}_{-166}\right) > 22$

→ Nb - like behaviour of $_{105}$Db in agreement with theoretical expectations under influence of relativistic effects

Sg



AQUEOUS CHEMSTRY WITH SEABORGIUM

one - atom - per - day liquid chromatography

- hexavalent ions; Sg (VI)
- member of group 6
- non U - like behaviour; no SgO_2^{2+}

- Mo, W - like behaviour in HNO_3 / HF - solution

  formation of neutral and / or anionic complexes

  SgO_2F_2 and / or $SgO_2F_3^-$ likely; no SgO_4^{2-}

- non W - like behaviour in pure HNO_3

  no formation of neutral or anionic complexes

  no SgO_4^{2-}

  formation of $Sg(OH)_4(H_2O)_2^{2+}$ and / or

  $Sg(OH)_5(H_2O)^+$ likely

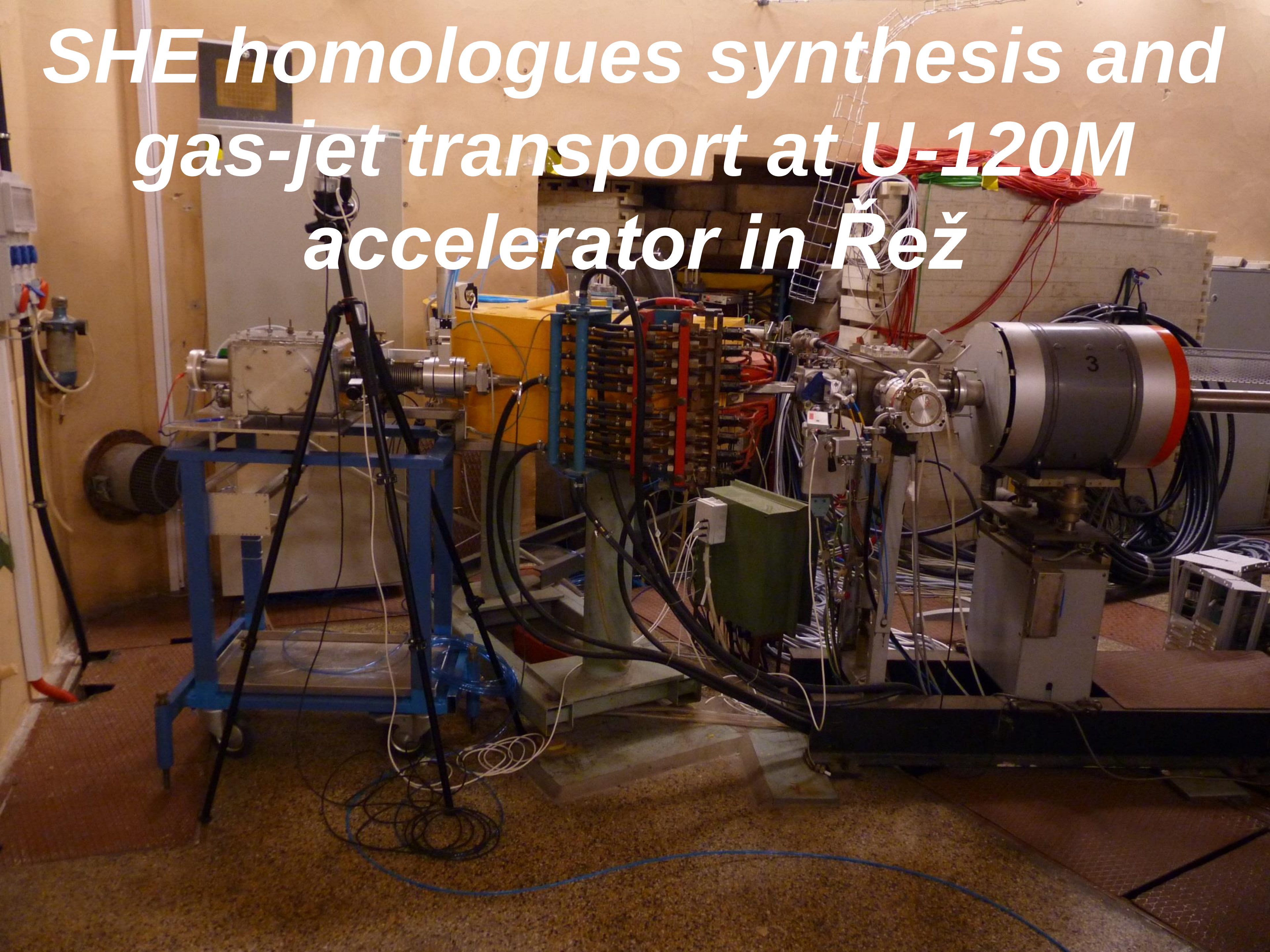
- decreasing hydrolysis: Mo > W > Sg

AQUEOUS CHEMISTRY OF TRANSACTINIDES

SUMMARY

- atom - at - a - time chemistry
- ${}_{104}$Rf, ${}_{105}$Db, ${}_{106}$Sg investigated
- members of group 4 to 6 of the PTE
- structure of the PTE is (still?) intact
- relativistic effects are strongly influencing the chemical properties
- chemical properties are - in detail - no more predictable with purely empirical methods
- chemical properties are - in detail - predictable combining empirical models with modern, relativistic molecular calculations

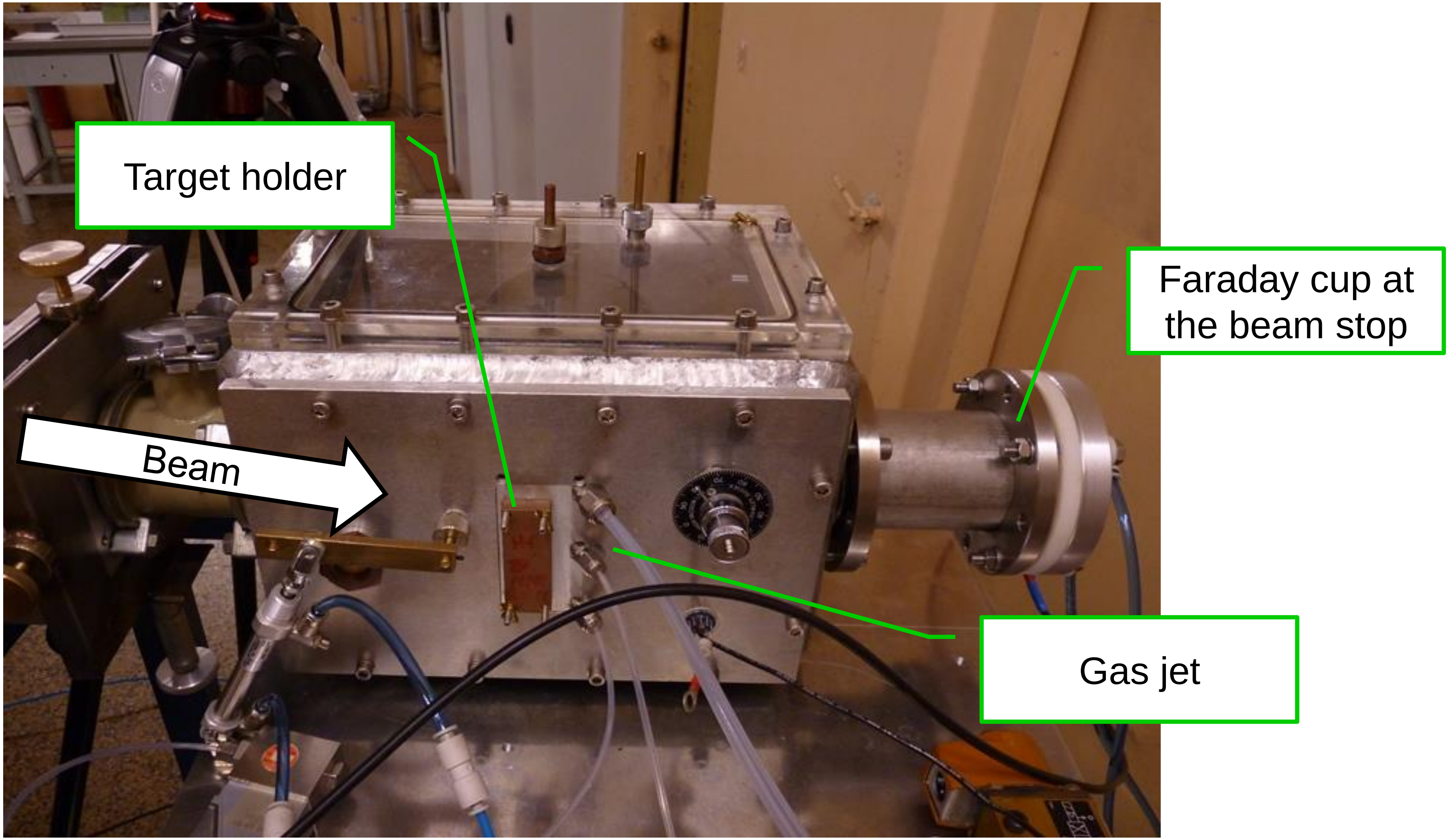
SHE homologues synthesis and gas-jet transport at U-120M accelerator in Řež



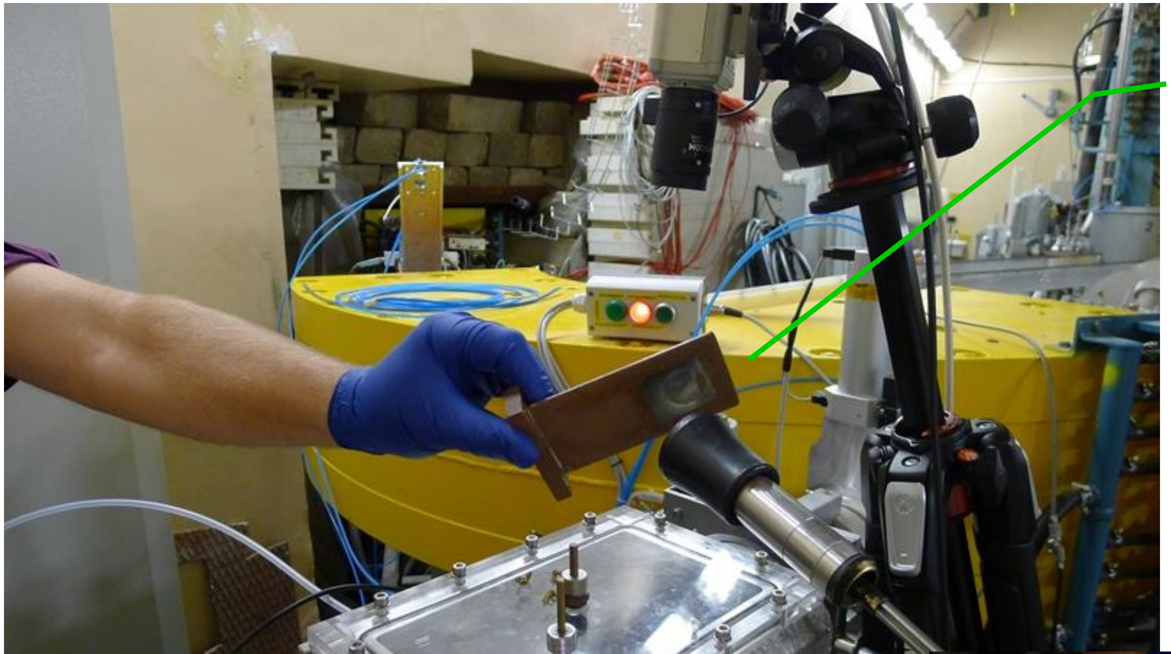
Experimental set-up – Řež

Target chamber at cyclotrone U-120

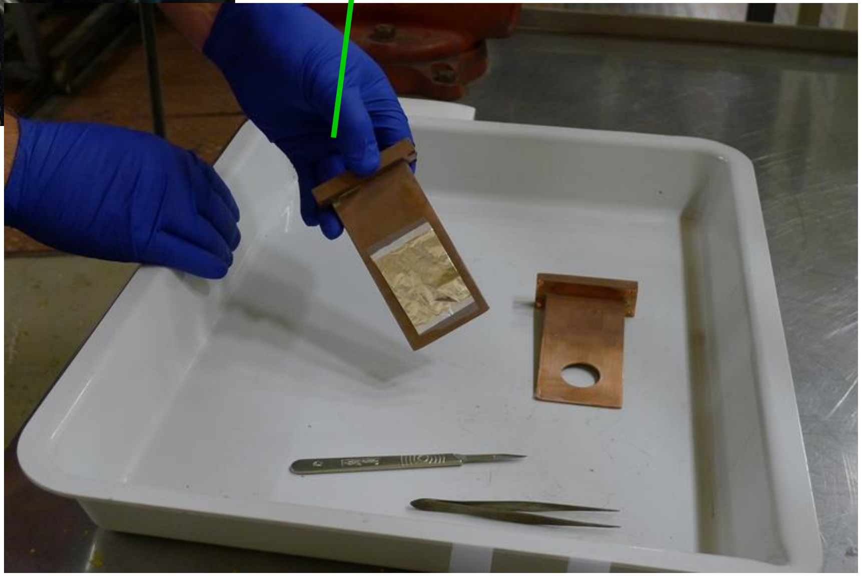
Cyclotron beam: 100-500 nA $^{3}He^{2+}$ @ 47 MeV



Experimental set-up – Řež



Target activity check



Removing the catcher foil

Experimental set-up – Řež

Aerosol: KCl cluster source – oven 620-680°C
Gas jet: He at 2 bar, 0.5 - 4 L/min

Oven with KCl

Pressure and gas flow control

Catcher filters

Temperature control

Gas Phase Chemistry with Transactinides

Gas Phase Chemistry Community:

PAUL SCHERRER INSTITUT
PSI

UNIVERSITÄT BERN

TECHNISCHE UNIVERSITÄT MÜNCHEN

INSTITUTE OF PHYSICS ACADEMIA SINICA

GSI

IMP

universität mainz

THE UNIVERSITY OF CALIFORNIA MERCED

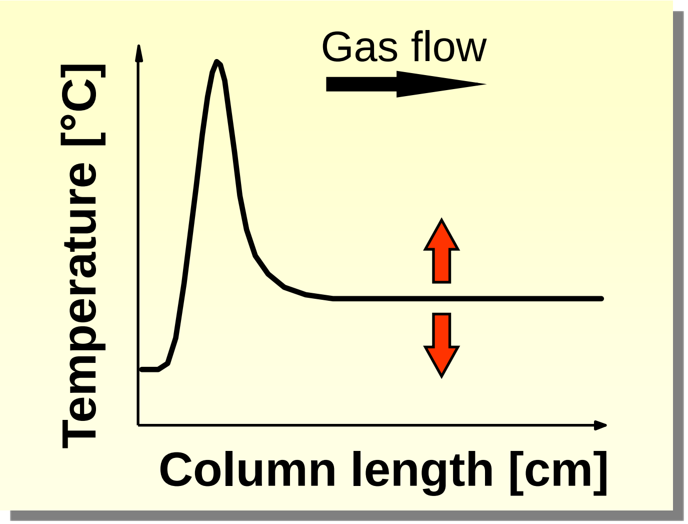
BERKELEY LAB

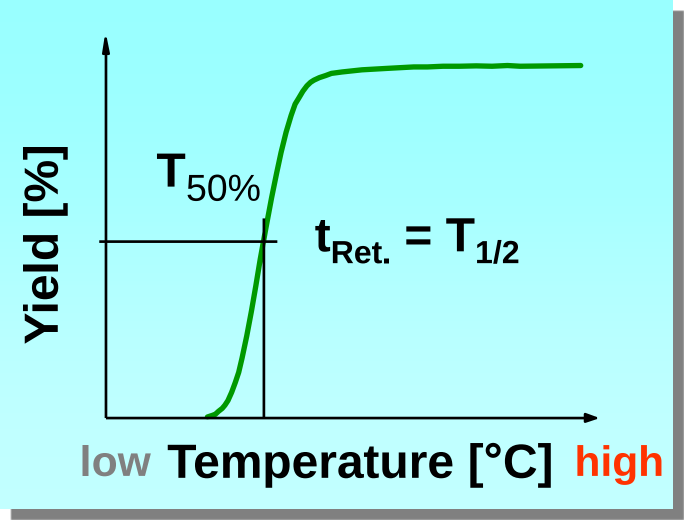
Japan Atomic Energy Research Institute
JAERI

ITE

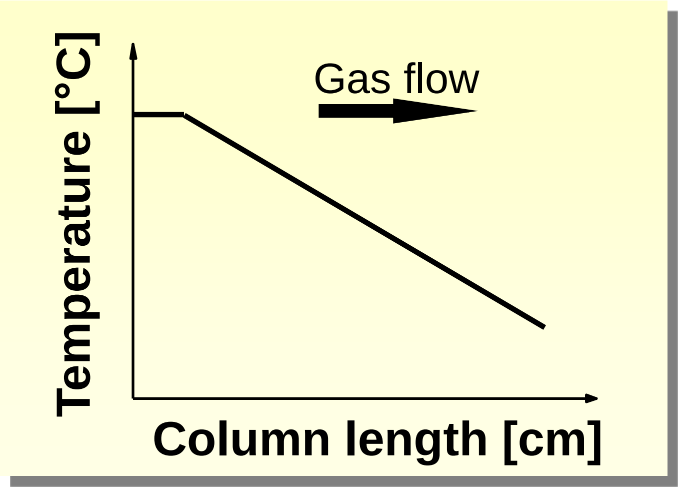
FZR

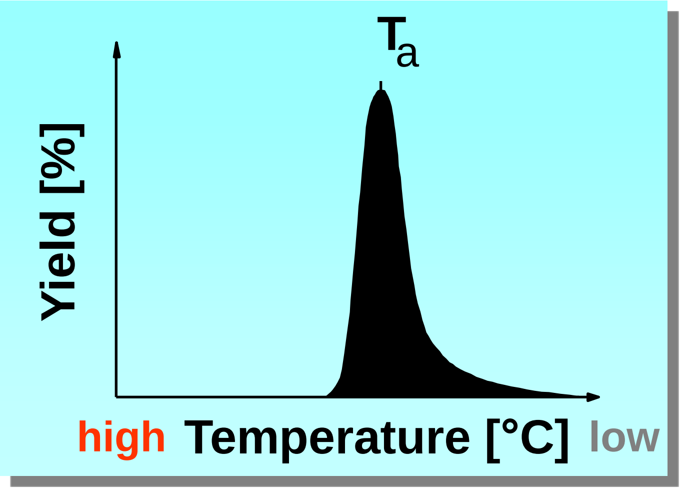
Isothermal Chromatography:





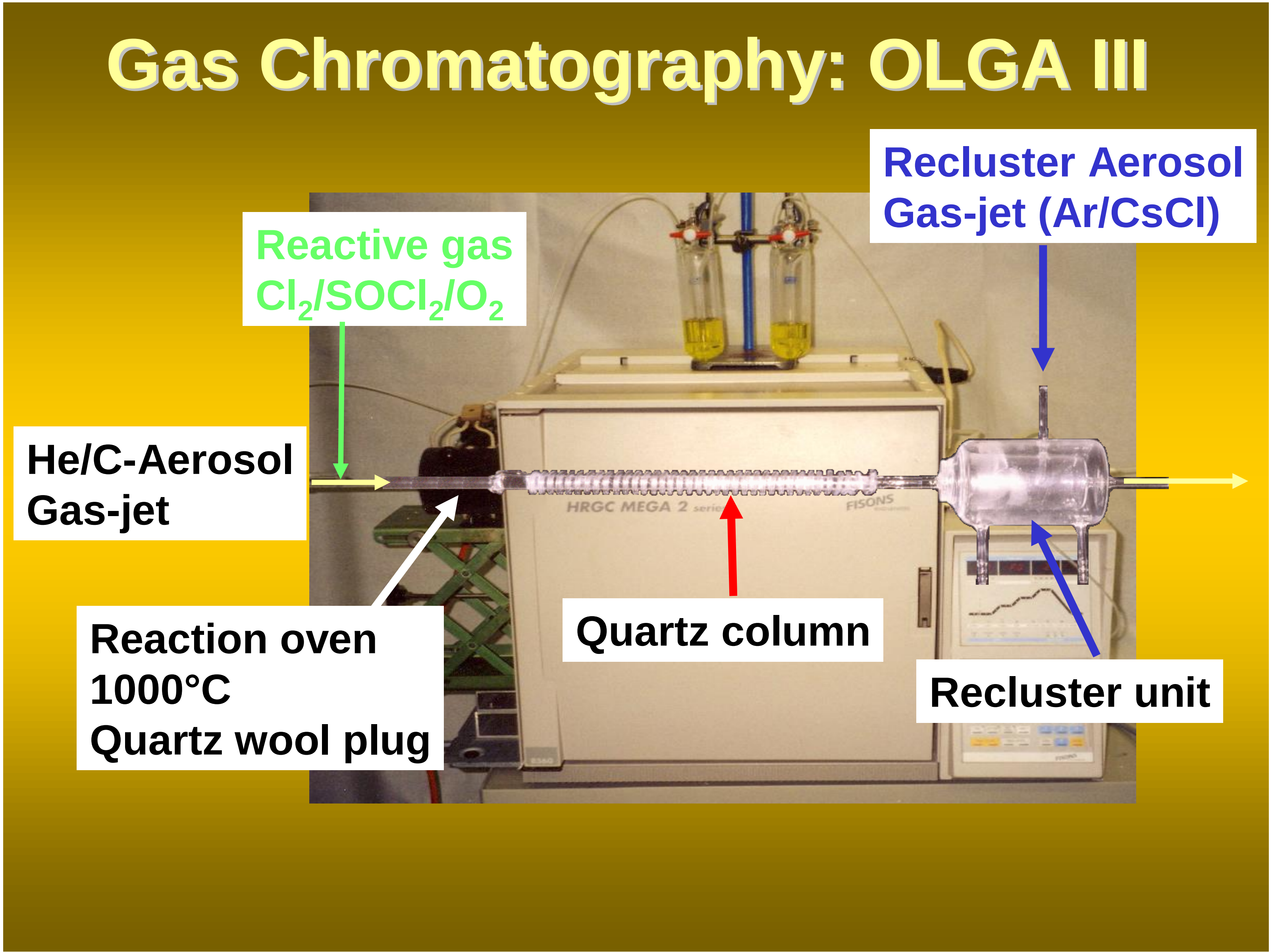
Thermochromatography:





OLGA

a device to measure retention temperatures of volatile species



Gas Chromatography: OLGA III

Recluster Aerosol
Gas-jet (Ar/CsCl)

Reactive gas
$Cl_2/SOCl_2/O_2$

He/C-Aerosol
Gas-jet

Reaction oven
1000°C
Quartz wool plug

Quartz column

Recluster unit

Working Hypothesis

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

*	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Working Hypothesis

Single atoms require simple stable molecules suitable for gas phase investigations

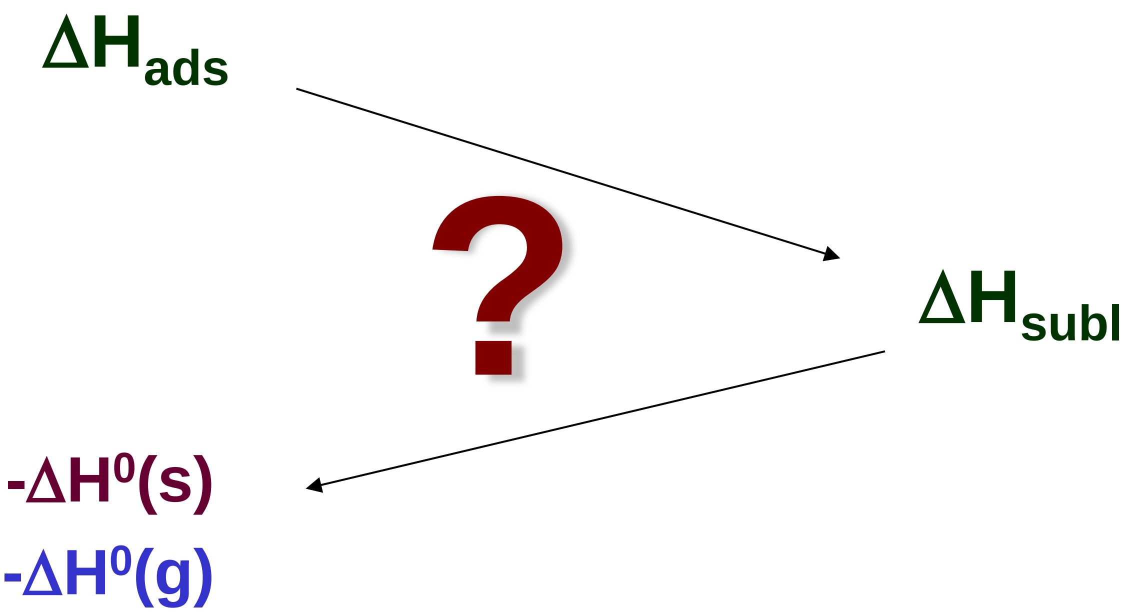
Element	Compound	Method/surface	Bond Character
Rf	$RfOX_2$, RfX_4	TC,IC / quartz	Chemisorption
Db	$DbOX_3$, DbX_5	TC,IC / quartz	Chemisorption
Sg	SgO_2X_2	TC,IC / quartz	Chemisorption
Bh	BhO_3X, BhO_3OH	IC / quartz	Chemisorption
Hs	HsO_4	TC / quartz	Chemisorption/Physisorption

X = halogen

Model experiments → single atoms of lighter homologues

“Microscopic-Macroscopic” Approach of Gas Phase Chemistry

Adsorption of single atoms / molecules



ΔH_{ads}

?

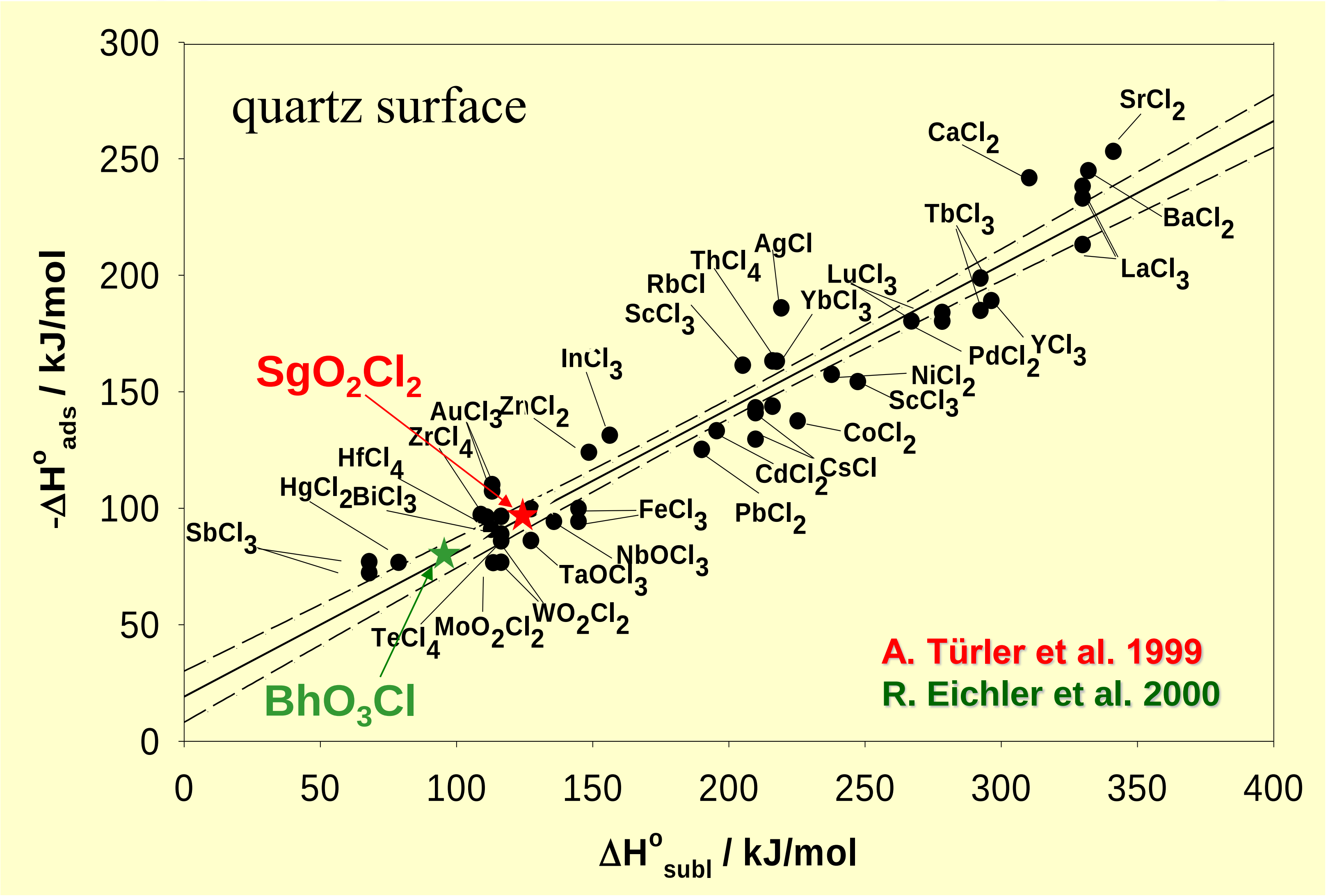
ΔH_{subl}

$-\Delta H^0(s)$

$-\Delta H^0(g)$

Stability of macroscopic phases

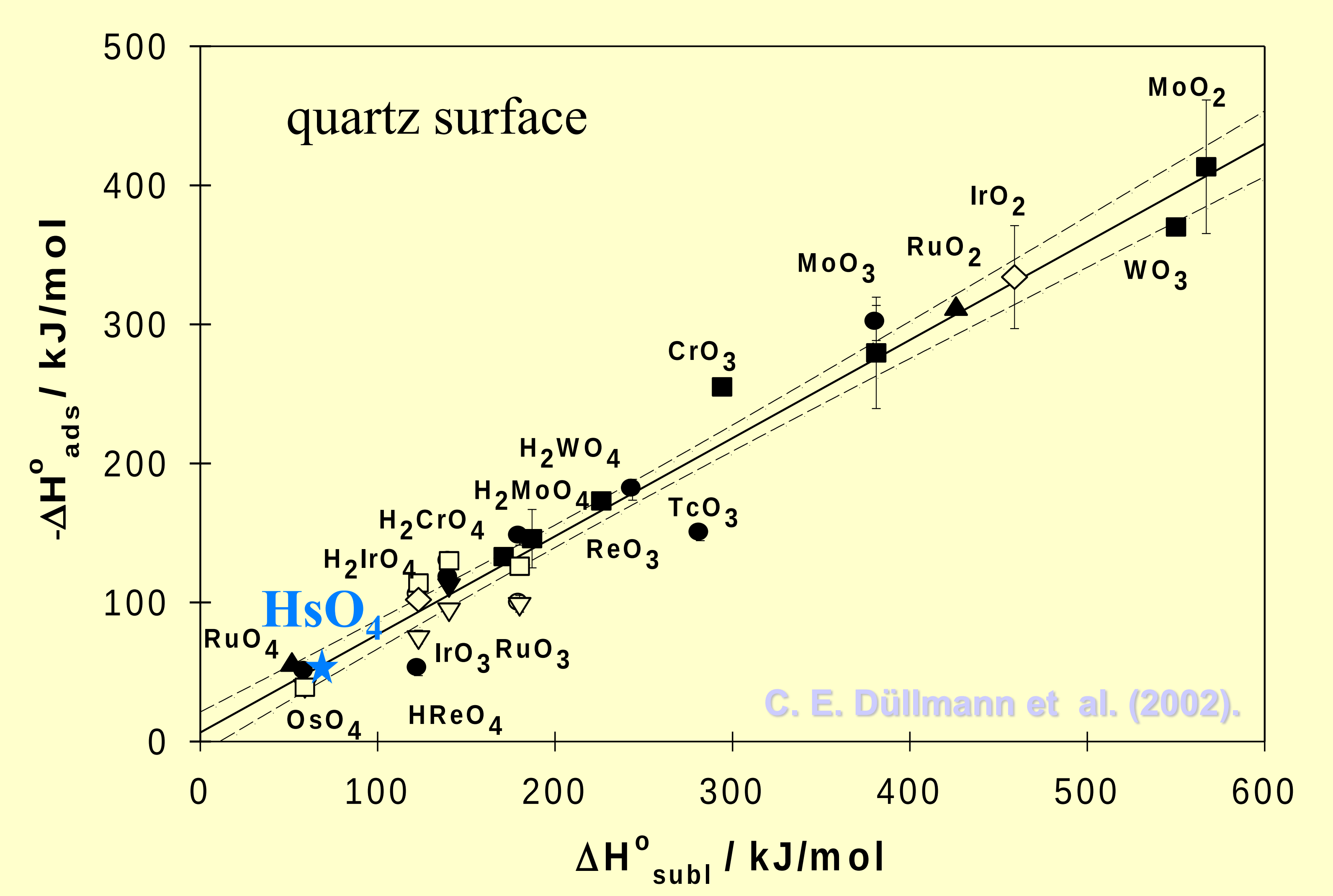
"Microscopic-Macroscopic" Approach of Gas Phase Chemistry



Eichler, B. et al.: J. Phys. Chem. A 103(46), 9296 (1999).

Halogenidy: $-\Delta H^o_{ads} = (21.5 \pm 5.2) + (0.600 \pm 0.025) \cdot \Delta H^o_{subl}$

“Microscopic-Macroscopic” Approach of Gas Phase Chemistry

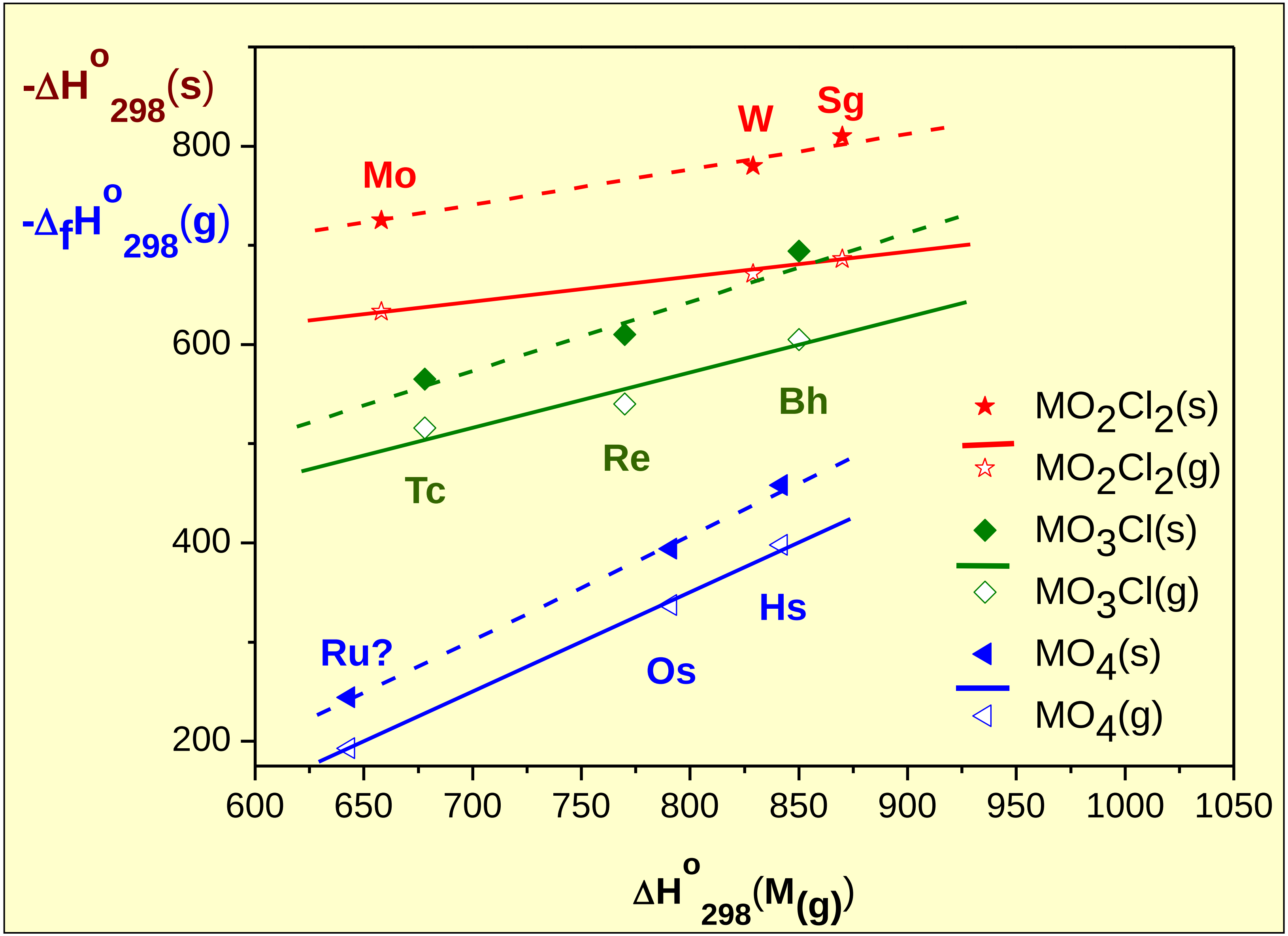


C. E. Düllmann et al. (2002).

R. Eichler et al. Radiochim. Acta 87, 151 (1999).

Oxidy: $-\Delta H^{o}_{ads} = (6.27 \pm 7.78) + (0.680 \pm 0.028) \cdot \Delta H^{o}_{subl}$

Results



$-\Delta H^o_{298}(s)$
$-\Delta_f H^o_{298}(g)$
800
600
400
200
W
Sg
Mo
Bh
Re
Tc
Ru?
Hs
Os
★ $MO_2Cl_2(s)$
☆ $MO_2Cl_2(g)$
◆ $MO_3Cl(s)$
◇ $MO_3Cl(g)$
◀ $MO_4(s)$
◁ $MO_4(g)$
600
650
700
750
800
850
900
950
1000
1050
$\Delta H^o_{298}(M_{(g)})$

107 – Bohrium (Bh)

Forecast: Eka-rhenium
1976: Dubna (Russia), Oganesyan et al.

$$^{209}\mathrm{Bi}(^{54}\mathrm{Cr},2n)^{261}107 \xrightarrow{20\%\ SF,\ 2\ ms;\ 80\%\ \alpha} {}^{257}\mathrm{Db} \xrightarrow{SF,\ 5\ s}$$

1981: GSI Darmstadt (Germany), Münzenberg, Armbruster et al.

$$^{209}\mathrm{Bi}(^{54}\mathrm{Cr},n)^{262}107 \xrightarrow{\alpha,\ 4.7\ ms} {}^{258}\mathrm{Db} \xrightarrow{\alpha} {}^{254}\mathrm{Lr} \xrightarrow{\alpha} {}^{250}\mathrm{Fm}$$

Position-sensitive SSB detectors – implantation
Proof: Whole decay chain in one pixel
6 atoms prepared

Today: A = 260-274 (some known only from the decay chains of higher TAn)
^{267}Bh $T_{1/2} = 17$ s α ^{249}Bk(^{22}Ne,4n)

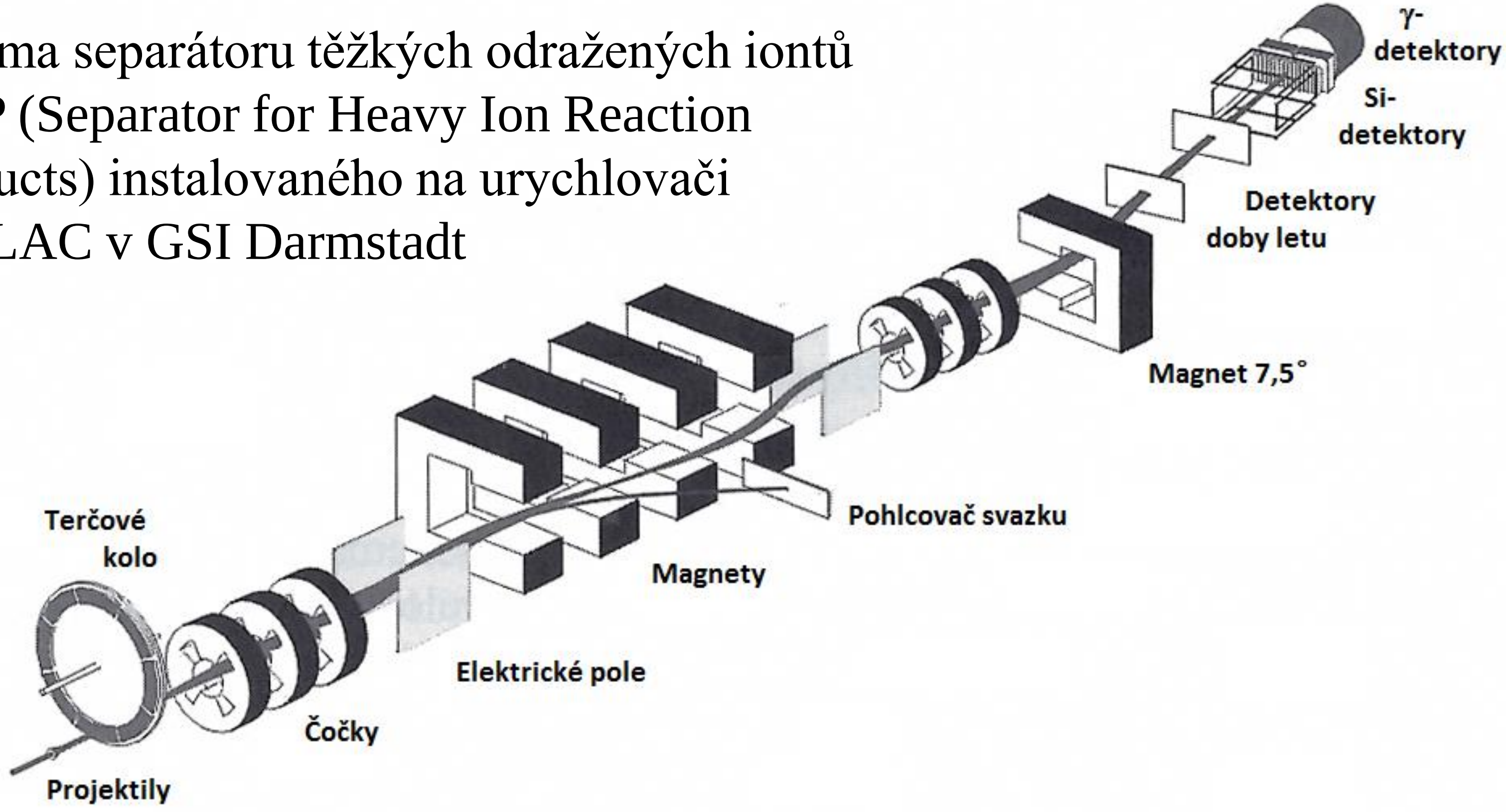
Chemistry
Theoretical forecast: similar to Re
Experimental: **PSI, 2000: chemistry with 6 atoms of ^{267}Bh, oxychlorides**
⇒ behaves like a typical group 7 of the PTE element
decreasing oxychloride volatility in group 7: $TcO_3Cl > ReO_3Cl >$ BhO Cl

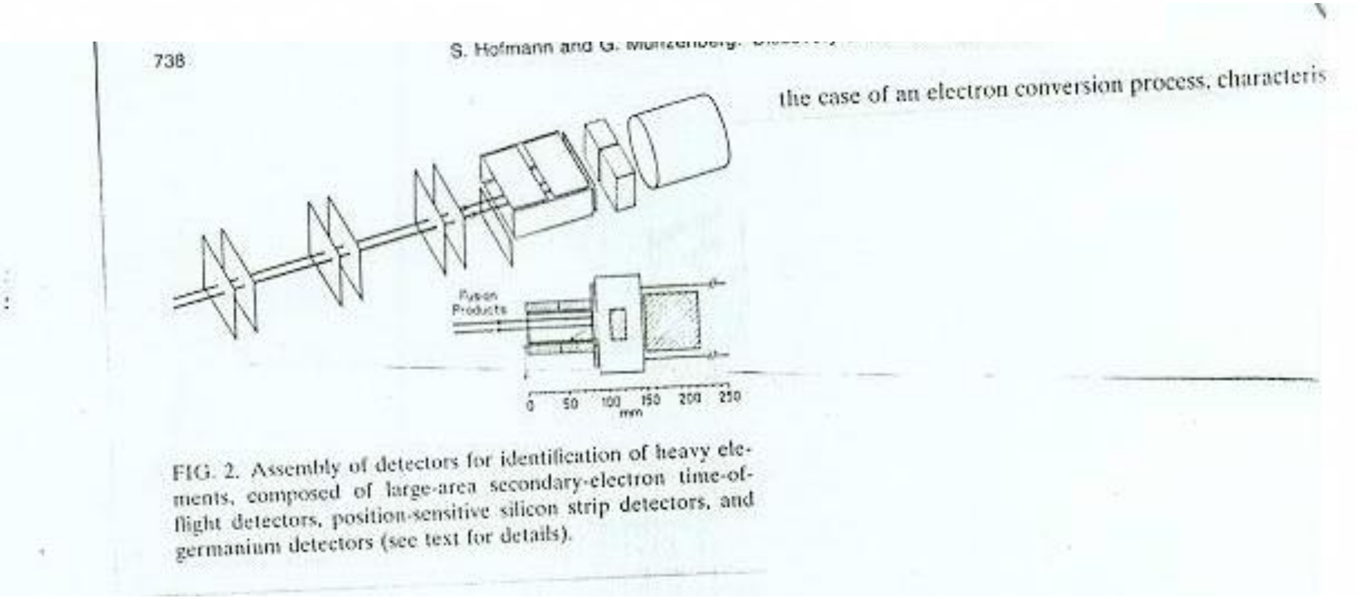
107 – Bohrium (Bh)

Main isotopes of bohrium

Isotope	Half-life	Decay mode	Product
^{278}Bh	690 s?	SF	
^{274}Bh	40 s	α	^{270}Db
^{272}Bh	10 s	α	^{268}Db
^{271}Bh	1 s	α	^{267}Db
^{270}Bh	60 s	α	^{266}Db
^{267}Bh	17 s	α	^{263}Db

Schéma separátoru těžkých odražených iontů SHIP (Separator for Heavy Ion Reaction Products) instalovaného na urychlovači UNILAC v GSI Darmstadt




738 S. Hofmann and G. Münzenberg:

the case of an electron conversion process, characteris

FIG. 2. Assembly of detectors for identification of heavy elements, composed of large-area secondary-electron time-of-flight detectors, position-sensitive silicon strip detectors, and germanium detectors (see text for details).

108 – Hassium (Hs)

Official discovery

First synthesized in 1984 by a German research team led by **Peter Armbruster** and **Gottfried Münzenberg** at the Gesellschaft für Schwerionenforschung in Darmstadt.

$$^{208}\mathrm{Pb}\,(^{58}\mathrm{Fe},n)\,^{265}\mathrm{Hs} \xrightarrow{\alpha,\,1.8\ \mathrm{ms}} \textbf{decay chain}$$

3 atoms detected in this experiment. IUPAC/IUPAP recognised the GSI as official discoverers in their 1992.

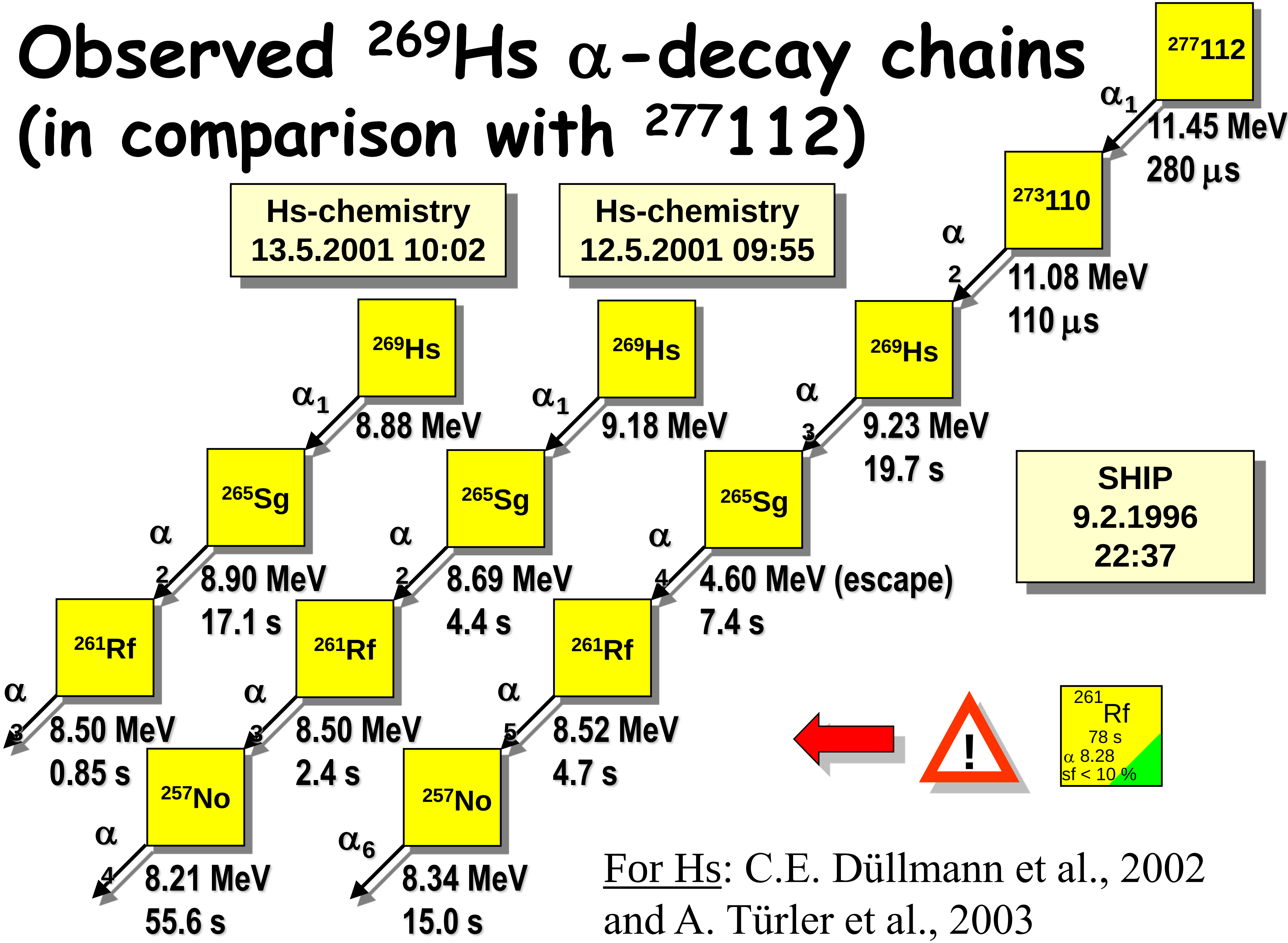
Naming

The name hassium derived from the Latin name for the German state of **Hessen** where the institute is located (Latin: hassia German: Hessen). Adopted internationally in 1997.

Chemistry

Expected to behave as ***eka-osmium***. Forecasted to form very volatile HsO_4 gaseous at a single-molecule level at ambient pressure and temperature (like OsO_4. Verified in gas chromatography experiments.

Observed ^{269}Hs α-decay chains (in comparison with ^{277}112)



Hs-chemistry 13.5.2001 10:02

^{269}Hs
α_1 8.88 MeV
^{265}Sg
α_2 8.90 MeV 17.1 s
^{261}Rf
α_3 8.50 MeV 0.85 s
^{257}No
α_4 8.21 MeV 55.6 s

Hs-chemistry 12.5.2001 09:55

^{269}Hs
α_1 9.18 MeV
^{265}Sg
α_2 8.69 MeV 4.4 s
^{261}Rf
α_3 8.50 MeV 2.4 s
^{257}No
α_6 8.34 MeV 15.0 s

SHIP 9.2.1996 22:37

^{277}112
α_1 11.45 MeV 280 μs
^{273}110
α_2 11.08 MeV 110 μs
^{269}Hs
α_3 9.23 MeV 19.7 s
^{265}Sg
α_4 4.60 MeV (escape) 7.4 s
^{261}Rf
α_5 8.52 MeV 4.7 s

!

^{261}Rf
78 s
α 8.28
sf < 10 %

For Hs: C.E. Düllmann et al., 2002 and A. Türler et al., 2003

108 – Hassium (Hs)

Main isotopes of hassium

Isotope	Half-life	Decay mode	Product
^{277}Hs	30 s	SF	
^{271}Hs	4 s	α	^{267}Sg
^{270}Hs	10 s	α	^{266}Sg
^{269}Hs	9.7 s	α	^{265}Sg

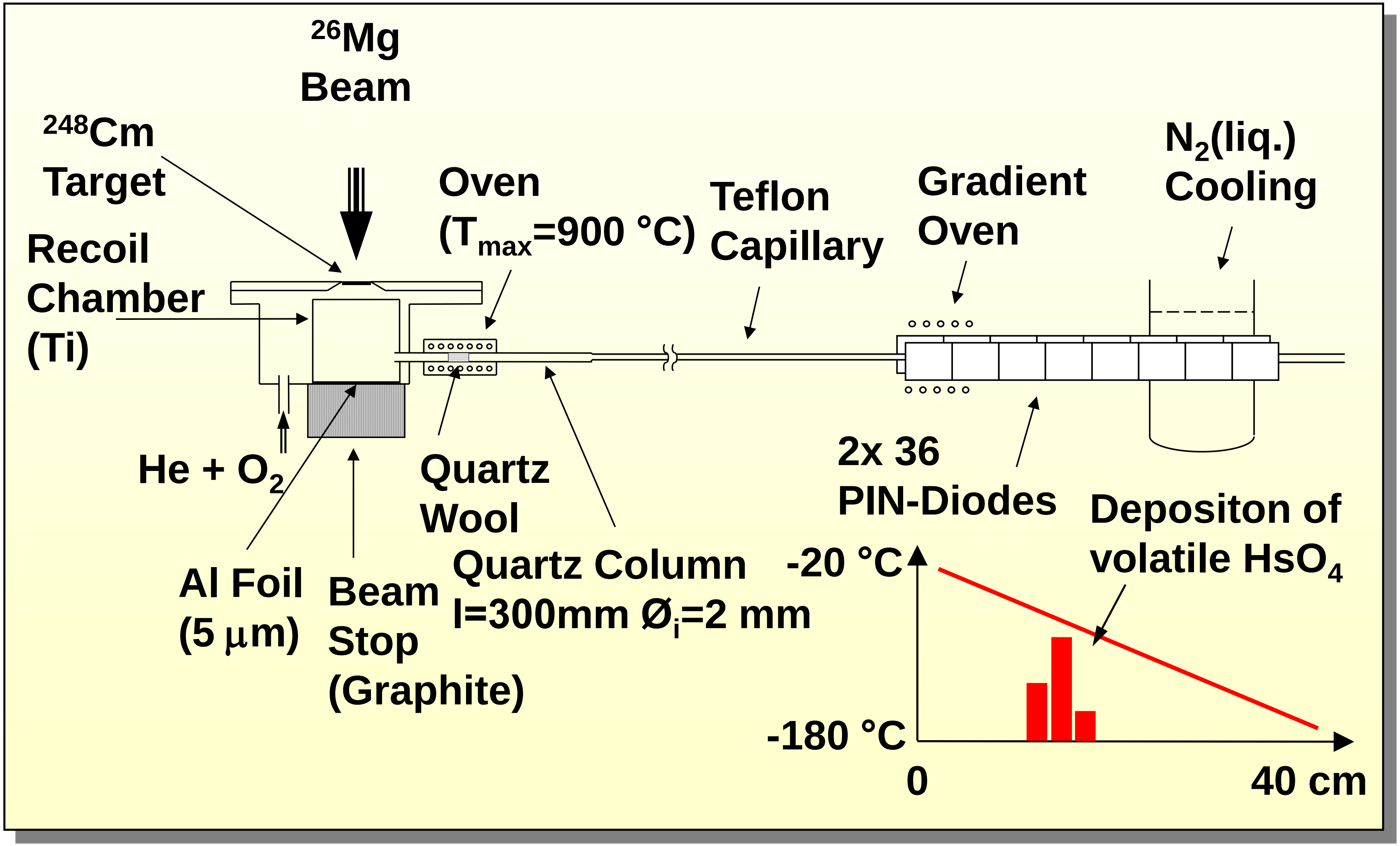
Experimental chemistry

HsO_4: ^{248}Cm(^{26}Mg,5n)^{269}Hs, 5 atoms, oxidized: $^{269}Hs + 2\ O_2 \rightarrow {}^{269}HsO_4$, thermochromatography ⇒ $\Delta H_{ads}(HsO_4) = (-46 \pm 2)$ kJ/mol ⇒ HsO_4 less volatile than OsO_4 ($\Delta H_{ads} = -39$ kJ/mol)

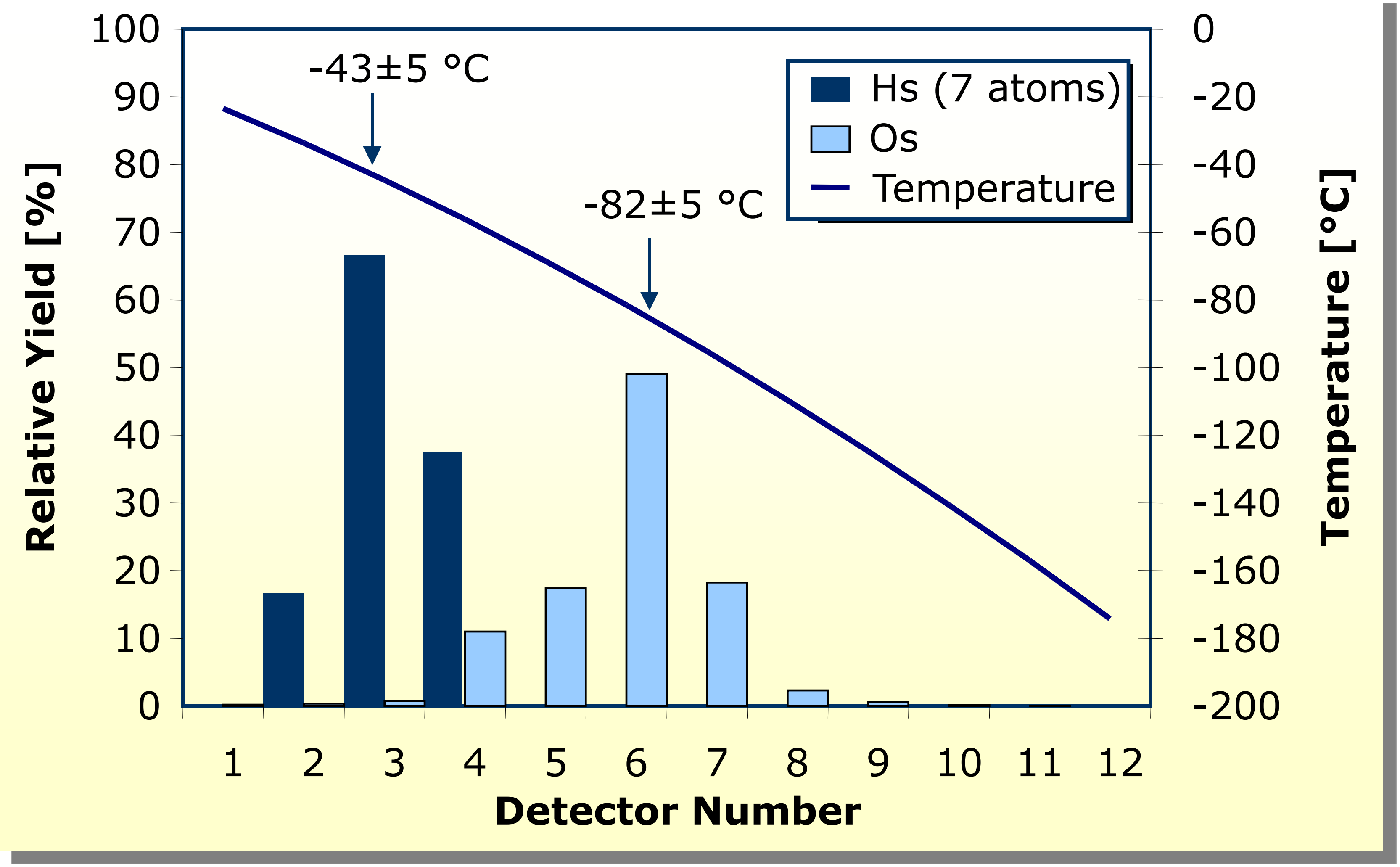
Hassate: Formed during deposition of HsO_4 on NaOH in the presence of water $HsO_4 + 2\ NaOH \rightarrow Na_2[HsO_4(OH)_2]$ – JGU Mainz, 2004

Future: prepare and study **hassocene**, $Hs(C_5H_5)_2$ – analogous to osmocene – cyclopentadienyl rings in an eclipsed conformation, hassium in the low formal oxidation state of +2

In-Situ Volatilization and On-line detection apparatus IVO



Thermochromatography of OsO_4 and HsO_4



SHE – Chemistry summary

Methods:

- Thermochromatography - OLGA at PSI
- HPLC – ARCA at GSI
- Liquid-liquid extraction – SISAK at Chalmers.

Results:

- Rf is a homologue of Zr and Hf (closer to Hf than Zr).
- Db behaves more like Nb than Ta. Similarity with pseudohomologue Pa.
- Sg resembles Mo, W and pseudohomologue U. Chemistry based on 2 atoms, difficults to draw final conclusions. The last element studied by aqueous chemistry.
- Bh studied only by thermochromatography –homologue of Tc and Re.
- Hs forms tetraoxide like Ru and Os. May also form hassate similar to rutenate or osmiate.
- Studies of Cn on the go.

109 – Meitnerium (Mt)

Official discovery

First synthesized on August 29, 1982 by a German team led by **Peter Armbruster** and **Gottfried Münzenberg** at the GSF Darmstadt.

$$^{209}\mathrm{Bi}\ (^{58}\mathrm{Fe},n)\ ^{266}\mathrm{Mt} \xrightarrow{\alpha,\ 3.5\ \mathrm{ms}}$$ **decay chain**

1 atom detected (!) in this experiment. Now: The most stable is ^{278}Mt ($T_{1/2}$ = 7.6 s)

Naming

The name meitnerium (Mt) was suggested in honor of the Austrian physicist Lise Meitner. In 1997, the name adopted by IUPAC.

Chemistry

Expected to behave as ***eka-iridium***. Sufficiently stable isotope is not known at this time which would allow to study chemical properties.

By analogy with the lighter members of group 9 meitnerium should:

- form a hexafluoride, MtF6, more stable than iridium(VI) fluoride
- show a dioxide, MtO2, if eka-iridium reactivity is shown
- form $MtCl_3$, $MtBr_3$ and MtI_3 in an analogous manner to iridium.

109 – Meitnerium (Mt)

Most stable isotopes			
iso	**half-life**	**DM**	**DE (MeV)**
^{278}Mt	7.6 s	α	9.6
^{276}Mt	0.72 s	α	9.71
^{275}Mt	9.7 ms	α	10.33
^{274}Mt	0.44 s	α	9.76
^{270m}Mt ?	1.1 s	α	
^{270g}Mt	5 ms	α	10.03
^{268}Mt	42 ms	α	10.26,10.10
^{266}Mt	1.7 ms	α	11.00

110 – Darmstadtium (Ds)

Official discovery

First synthesized on November 9, 1994 by a German team led by **P. Armbruster** and **G. Münzenberg** (+Šáro, Janík) at the GSF Darmstadt.

$^{208}\mathrm{Pb}\ (^{62}\mathrm{Ni},n)\ ^{269}\mathrm{Ds} \xrightarrow{\alpha,\ 170^{+160}_{-60}\ \mu s}$ **decay chain**

$^{208}\mathrm{Pb}\ (^{64}\mathrm{Ni},n)\ ^{271}\mathrm{Ds} \xrightarrow{\alpha,\ 1.1^{+0.6}_{-0.3}\ \mu s}$ **decay chain**

4 or 3 atoms of ^{269}Ds or ^{271}Ds detected, respectively in these experiments. IUPAC/IUPAP recognised the GSI as official discoverers in 2001.

Naming

The team at GSI considered the names Darmstadtium (Ds) and Wixhausium (Wi). They decided on the former and named the element after the city near the place of its discovery, Darmstadt and not the suburb Wixhausen itself. The new name was officially recommended by IUPAC on August 16, 2003.
Earlier alternate proposals: Hahnium (US), Becquerelium (Russia).

110 – Darmstadtium (Ds)

Chemistry

Expected to behave as ***eka-platinum***. Sufficiently stable isotope is not known at this time which would allow to study chemical properties. By analogy with the lighter members of group 10 Ds is:

- expected to form a stable hexafluoride, DsF_6, in addition to DsF_5 and DsF_4
- halogenation should result in the formation of tetrahalides, $DsCl_4$, $DsBr_4$, and DsI_4.

It can be expected to have notable hardness and catalytic properties

Main isotopes of darmstadtium

Isotope	Half-life	Decay mode	Product
^{281}Ds	14 s	94% SF	
		6% α	^{277}Hs
^{279}Ds	0.2 s	10% α	^{275}Hs
		90% SF	

111 – Roentgenium (Rg)

Official discovery

First synthesized on December 8, 1994 by a German team led by **Sigurd Hofmann** at the GSF Darmstadt.

$^{209}\mathrm{Bi}\ (^{64}\mathrm{Ni},n)\ ^{272}\mathrm{Rg} \xrightarrow{\alpha,\ 1.1^{+0.6}_{-0.3}\ \mu s}$ **decay chain**

3 atoms of ^{272}Rg detected in this experiment. IUPAC/IUPAP recognised the GSI as official discoverers in 2003 after preparation of 3 more atoms in 2002.

Naming

The name roentgenium (Rg) was proposed by the GSI team in honor of the German physicist Wilhelm Conrad Röntgen, and was accepted as a permanent name on November 1, 2004

111 – Roentgenium (Rg)

Chemistry

Expected to behave as ***eka-gold***. The heavier members of this group are well known for their lack of reactivity or noble character – inert to oxygen but are attacked by the halogens. Roentgenium is expected to be

- even more noble than gold
- be expected to be inert to oxygen and halogens
- expected to form $Rg(CN)_2^-$ complex
- the most-likely reaction is with fluorine to form a trifluoride, RgF_3.

No experimental chemistry, yet – low yield of Rg isotopes production.

Main isotopes of roentgenium

Isotope	Half-life	Decay mode	Product
^{286}Rg	10.7 min?	α	^{282}Mt
^{283}Rg	5.1 min?	SF	
^{282}Rg	2 min	α	^{278}Mt
^{281}Rg	17 s	SF (90%)	
		α (10%)	^{277}Mt
^{280}Rg	4 s	α	^{276}Mt
^{279}Rg	0.1 s	α	^{275}Mt

112 – Copernicium (Cn)

Official discovery

First synthesized on February 9, 1996 by a German team led by **Sigurd Hofmann, Victor Ninov et al.** at the GSF Darmstadt.

$$^{208}\mathrm{Pb}\,(^{70}\mathrm{Zn},n)\ ^{277}\mathrm{Cn} \xrightarrow{\alpha,\ 0.7\ \mathrm{ms}} \text{decay chain}$$

1 atom of ^{277}Cn detected in this experiment, a second was reported but data was fabricated by Ninov, another atom synthesised only in in 2000. Confirmed in Japan (RIKEN) in 2004. IUPAC/IUPAP recognised the GSI as official discoverers in May 2009 after GSF confirmed data for ^{269}Hs and ^{261}Rf.

Naming

Copernicium proposed by the GSI team with the symbol Cp, after Nicolaus Copernicus. However, Cp previously associated with the cassiopeium, now known as lutetium (Lu). IUPAC prompted the GSI team to the symbol Cn.

Name and symbol officially accepted by IUPAC on 19 February 2010, the 537th anniversary of Copernicus' birth.

112 – Copernicium (Cn)

Chemistry - predictions

Last member of the 6d series of transition metals and the heaviest group 12 element, below zinc, cadmium and mercury (***eka-mercury)***.

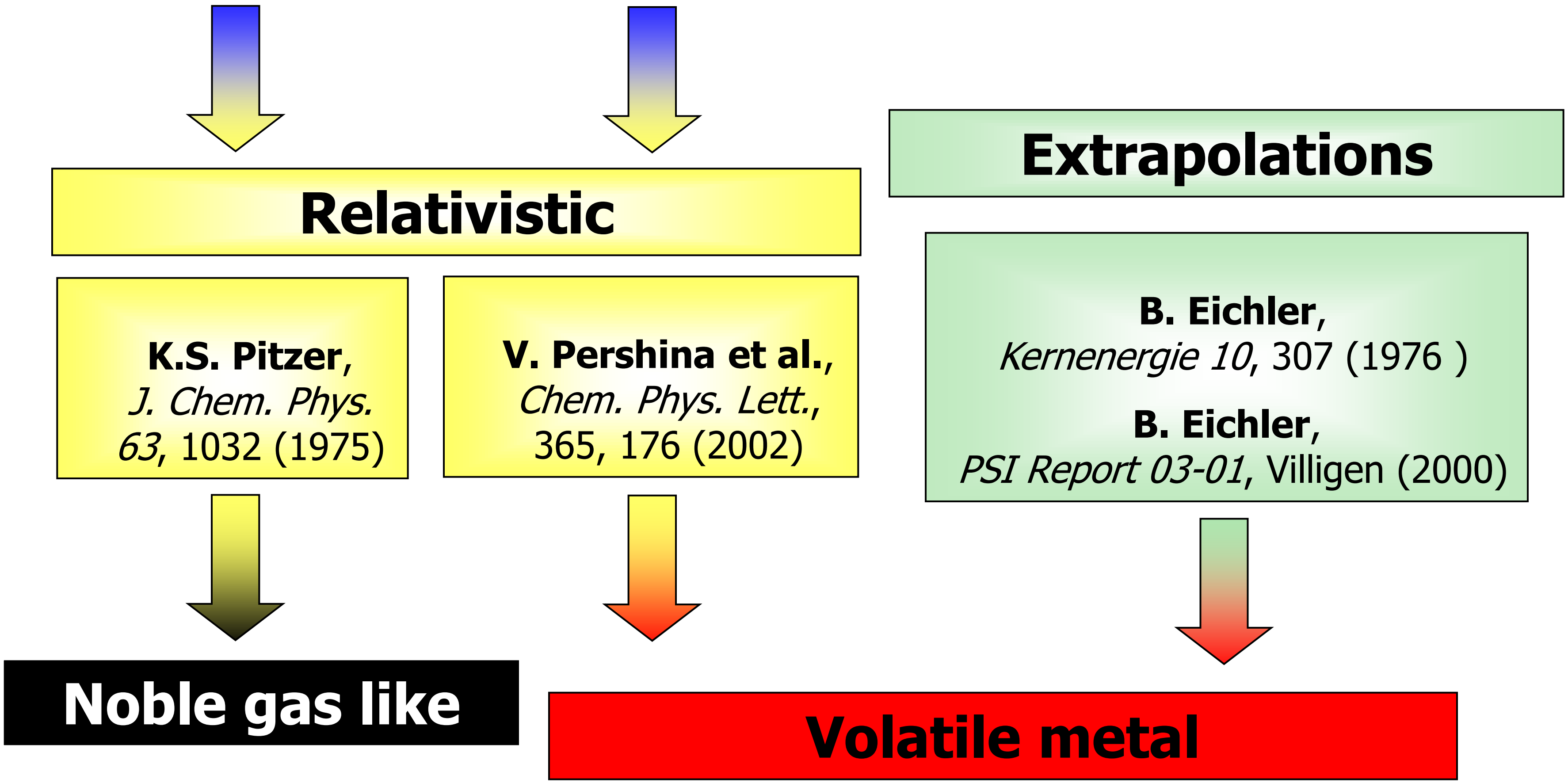
However, **predicted to differ significantly from lighter group 12 elements**. Due to the **largest relativistic effects** in the period 7, and among all 118 known elements

- in water solutions copernicium is likely to form +2 and +4 oxidation states, with the latter one being more stable
- may even behave as a rare gas – gaseous at standard temperature and pressure!

Main isotopes of copernicium

Isotope	Half-life	Decay mode	Product
^{286}Cn	8.45 s ?	SF	–
^{285}Cn	**30 s**	**α**	**^{281}Ds**
^{283}Cn	4 s	90% α	^{279}Ds
		10% SF	–

Predictions for element 112



Relativistic

K.S. Pitzer,
J. Chem. Phys. 63, 1032 (1975)

V. Pershina et al.,
Chem. Phys. Lett., 365, 176 (2002)

Extrapolations

B. Eichler,
Kernenergie 10, 307 (1976)

B. Eichler,
PSI Report 03-01, Villigen (2000)

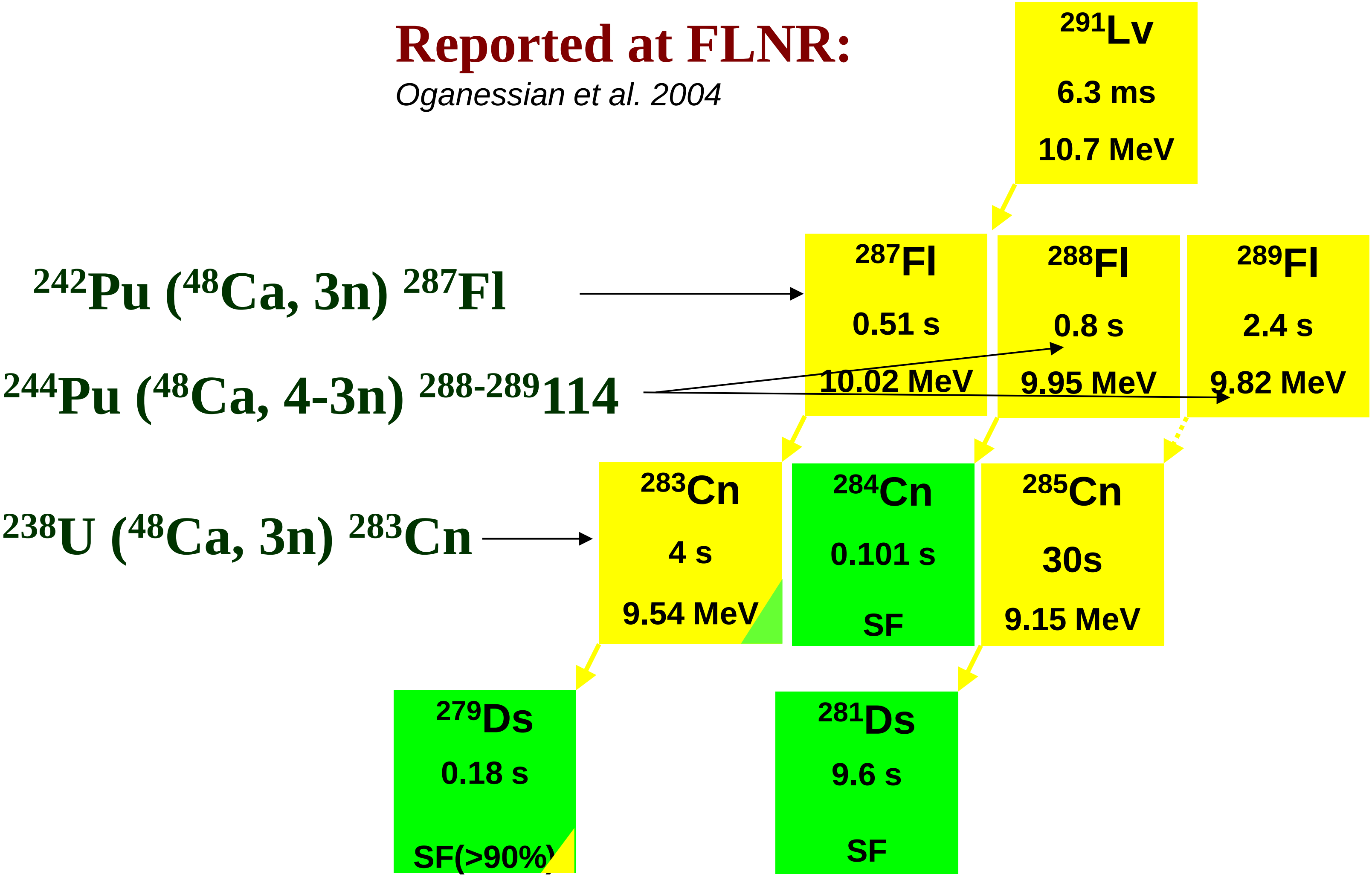
Noble gas like

Volatile metal

Copernicium and Flerovium Production

Reported at FLNR:

Oganessian et al. 2004



^{242}Pu (^{48}Ca, 3n) ^{287}Fl

^{244}Pu (^{48}Ca, 4-3n) $^{288\text{-}289}$114

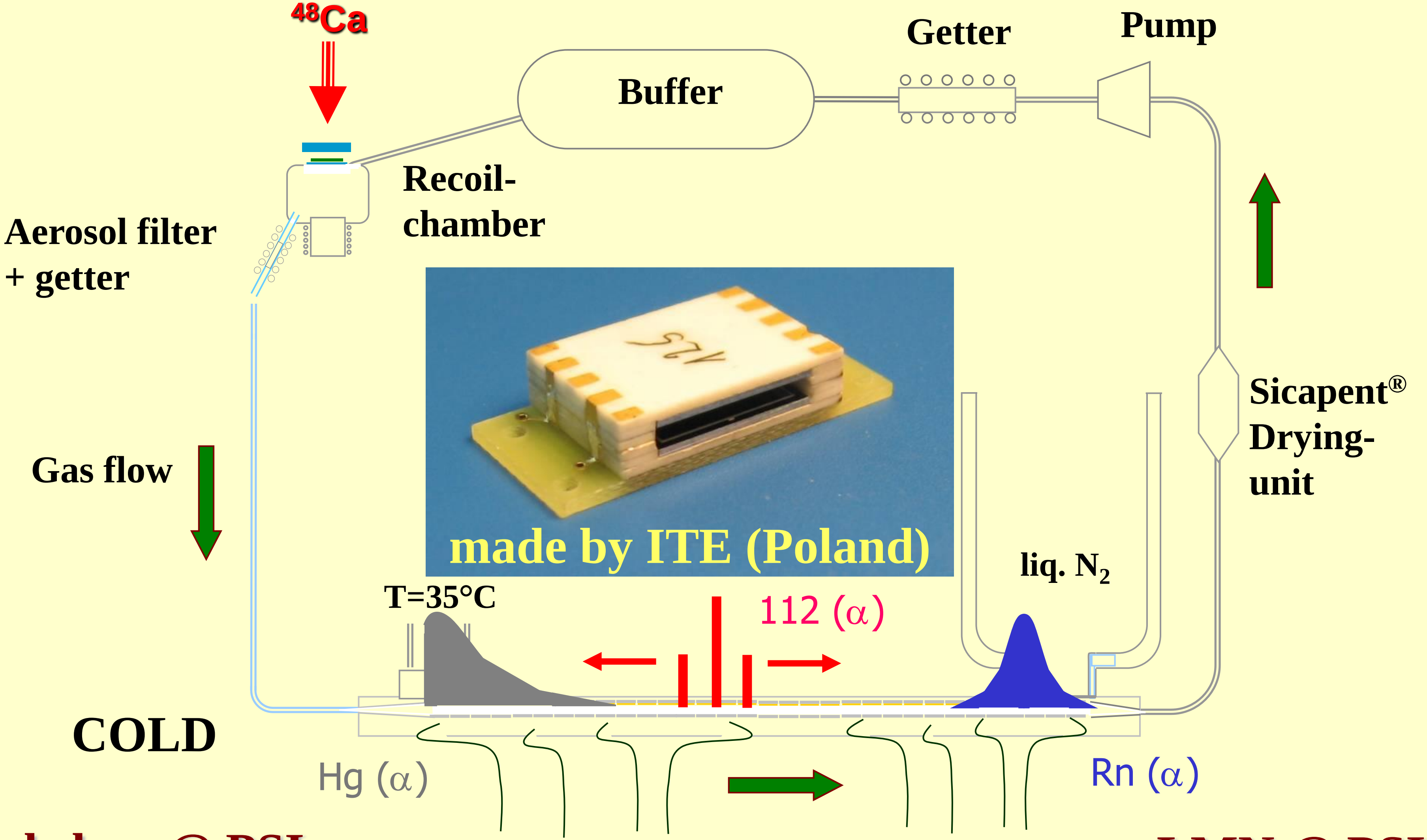
^{238}U (^{48}Ca, 3n) ^{283}Cn

Oganessian, Yu. Ts. Phys. Rev. C (2004)

Experimental Setup @ FLNR

workshop @ Uni Bern

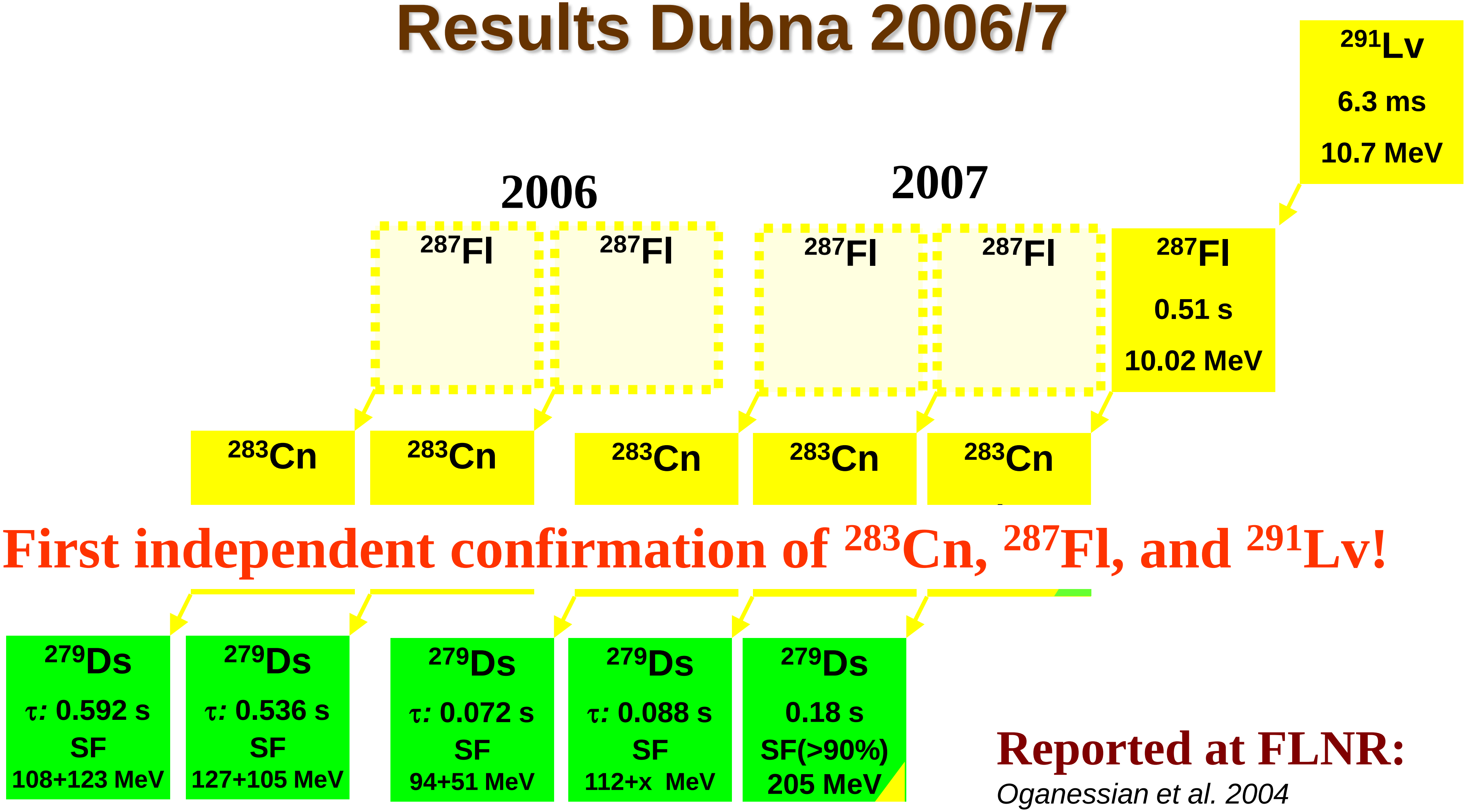
Electronics @ PSI



workshop @ PSI

LMN @ PSI

Results Dubna 2006/7



^{291}Lv
6.3 ms
10.7 MeV

2006

2007

^{287}Fl

^{287}Fl

^{287}Fl

^{287}Fl

^{287}Fl
0.51 s
10.02 MeV

^{283}Cn

^{283}Cn

^{283}Cn

^{283}Cn

^{283}Cn

First independent confirmation of ^{283}Cn, ^{287}Fl, and ^{291}Lv!

^{279}Ds
τ: 0.592 s
SF
108+123 MeV

^{279}Ds
τ: 0.536 s
SF
127+105 MeV

^{279}Ds
τ: 0.072 s
SF
94+51 MeV

^{279}Ds
τ: 0.088 s
SF
112+x MeV

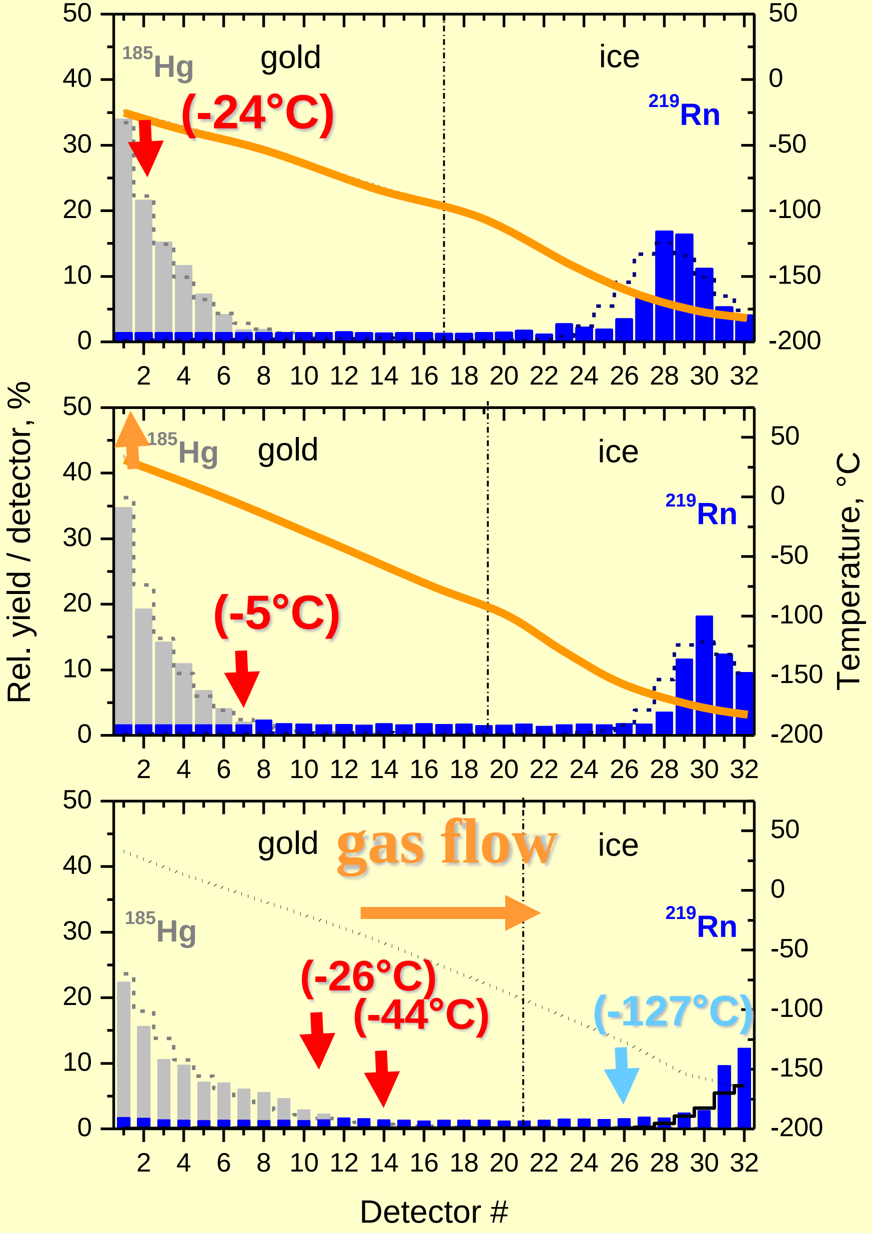
^{279}Ds
0.18 s
SF(>90%)
205 MeV

Reported at FLNR:
Oganessian et al. 2004

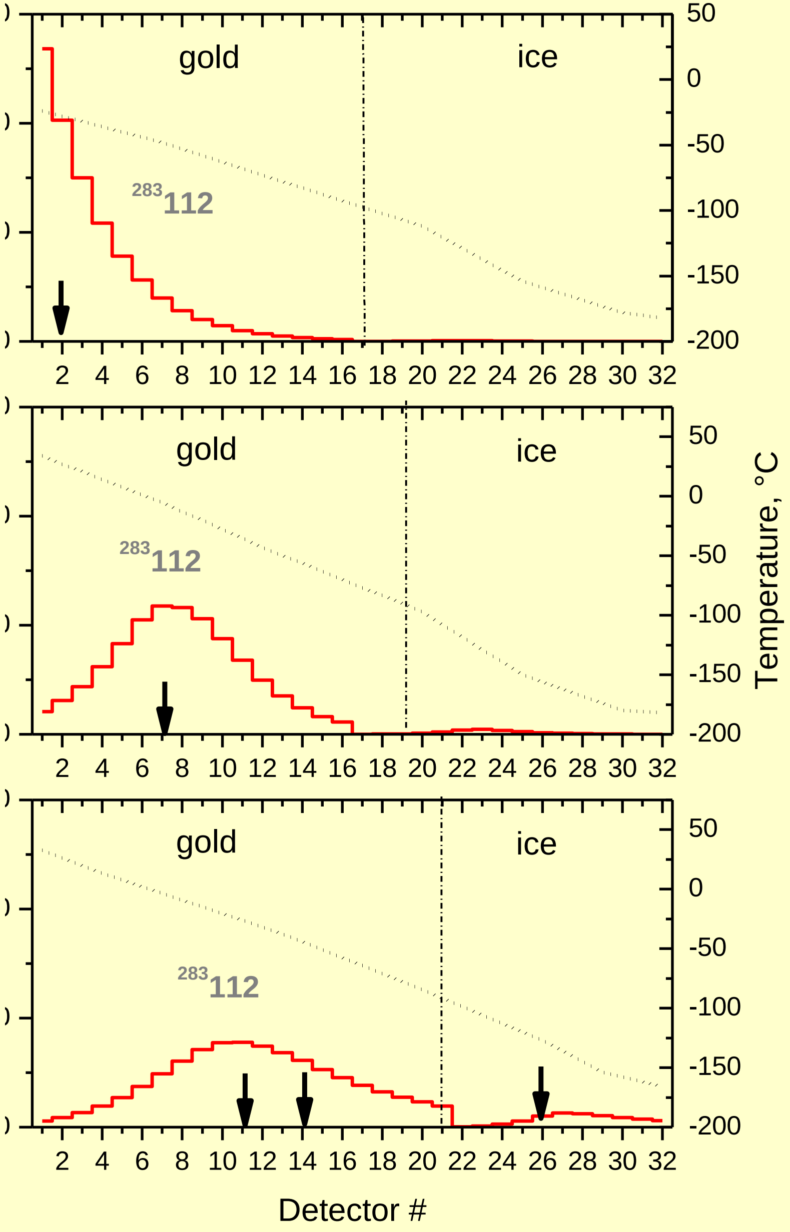
R. Eichler et al 2006

Results

Experiment

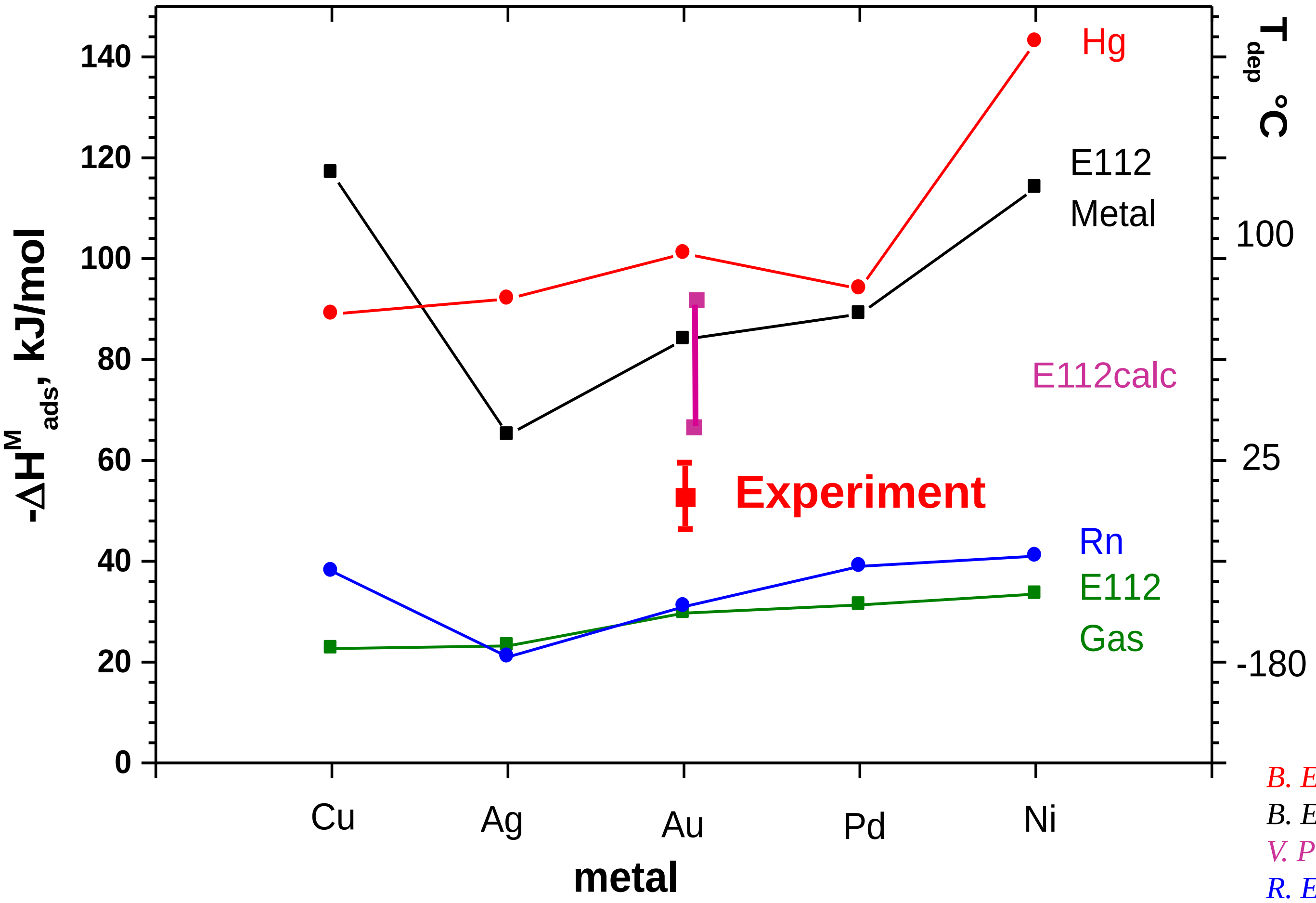


Simulation



Results

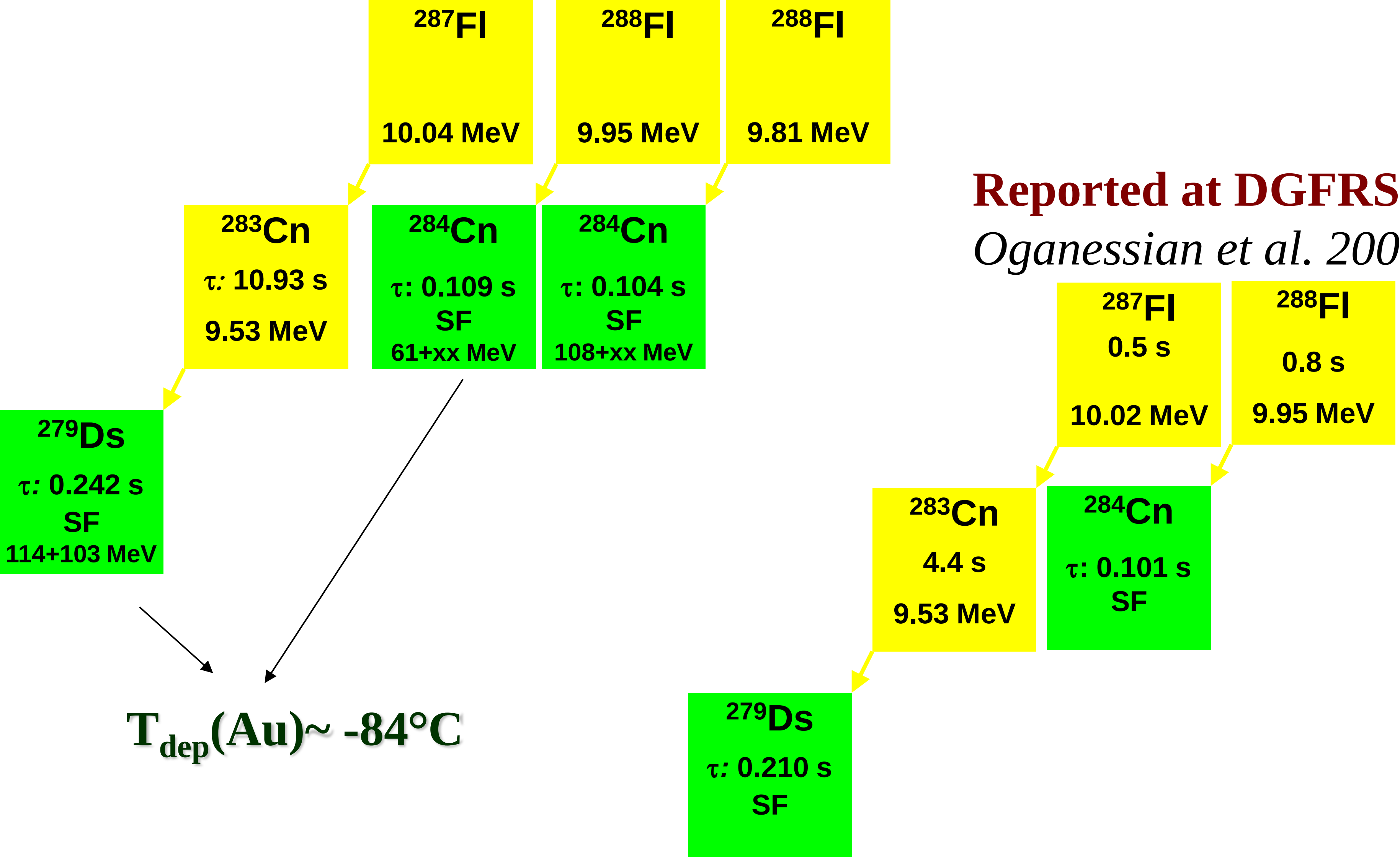
Cn adsorption on Au



B. Eichler 1985
B. Eichler 2003
V. Pershina et al. 2006
R. Eichler et al. 2002
R. Eichler et al. 2002

Results

Dubna 2007



Target: ^{242}Pu ^{244}Pu

^{287}Fl
10.04 MeV

^{288}Fl
9.95 MeV

^{288}Fl
9.81 MeV

^{283}Cn
τ: 10.93 s
9.53 MeV

^{284}Cn
τ: 0.109 s
SF
61+xx MeV

^{284}Cn
τ: 0.104 s
SF
108+xx MeV

^{279}Ds
τ: 0.242 s
SF
114+103 MeV

T_{dep}(Au)~ -84°C

Reported at DGFRS:

Oganessian et al. 2004

^{287}Fl
0.5 s
10.02 MeV

^{288}Fl
0.8 s
9.95 MeV

^{283}Cn
4.4 s
9.53 MeV

^{284}Cn
τ: 0.101 s
SF

^{279}Ds
τ: 0.210 s
SF

113 – Nihonium (Nh)

Official discovery

First detected in August 2003 as a decay product of Moscovium (Mc) by joint Dubna and LLNL teams lead by **S. Dmitriev**.

$$^{243}\mathrm{Am}\ (^{48}\mathrm{Ca},3\text{-}4n)\ ^{288,287}\mathrm{Mc} \rightarrow\ ^{284,283}\mathrm{Nh} \xrightarrow{\alpha,} \text{decay chain}$$

First synthesized (1 atom) on July 23, 2004 by a Japanese team at RIKEN lead by **Morita**. Another atom synthesized in 2012 (450 days of irradiation) – identification by the decay chain.

$$^{209}\mathrm{Bi}\ (^{70}\mathrm{Zn},n)\ ^{278}\mathrm{Nh} \xrightarrow{\alpha,} \text{decay chain}$$

Naming

The element with atomic number 113 is historically known as ***eka-thallium***.
The name Nihonium (Nh) name comes from the common Japanese name for Japan (日本 nihon).

113 – Nihonium (Nh)

List of nihonium isotopes

Isotope	Half-life	Decay mode	Discovery year	Reaction
^{278}Nh	1. 4 ms	α	2004	^{209}Bi(^{70}Zn,n)
^{282}Nh	70 ms	α	2006	^{237}Np(^{48}Ca,3n)
^{283}Nh	0.1 s	α	2003	^{287}Mc(—,α)
^{284}Nh	1 s	α, EC	2003	^{288}Mc(—,α)
^{285}Nh	**4 s**	**α**	**2009**	**^{293}Ts(—,2α)**
^{286}Nh	**8 s**	**α**	**2009**	**^{294}Ts(—,2α)**
^{287}Nh	5.5 s?	α	1999	^{287}Fl(e^-,ν_e)?

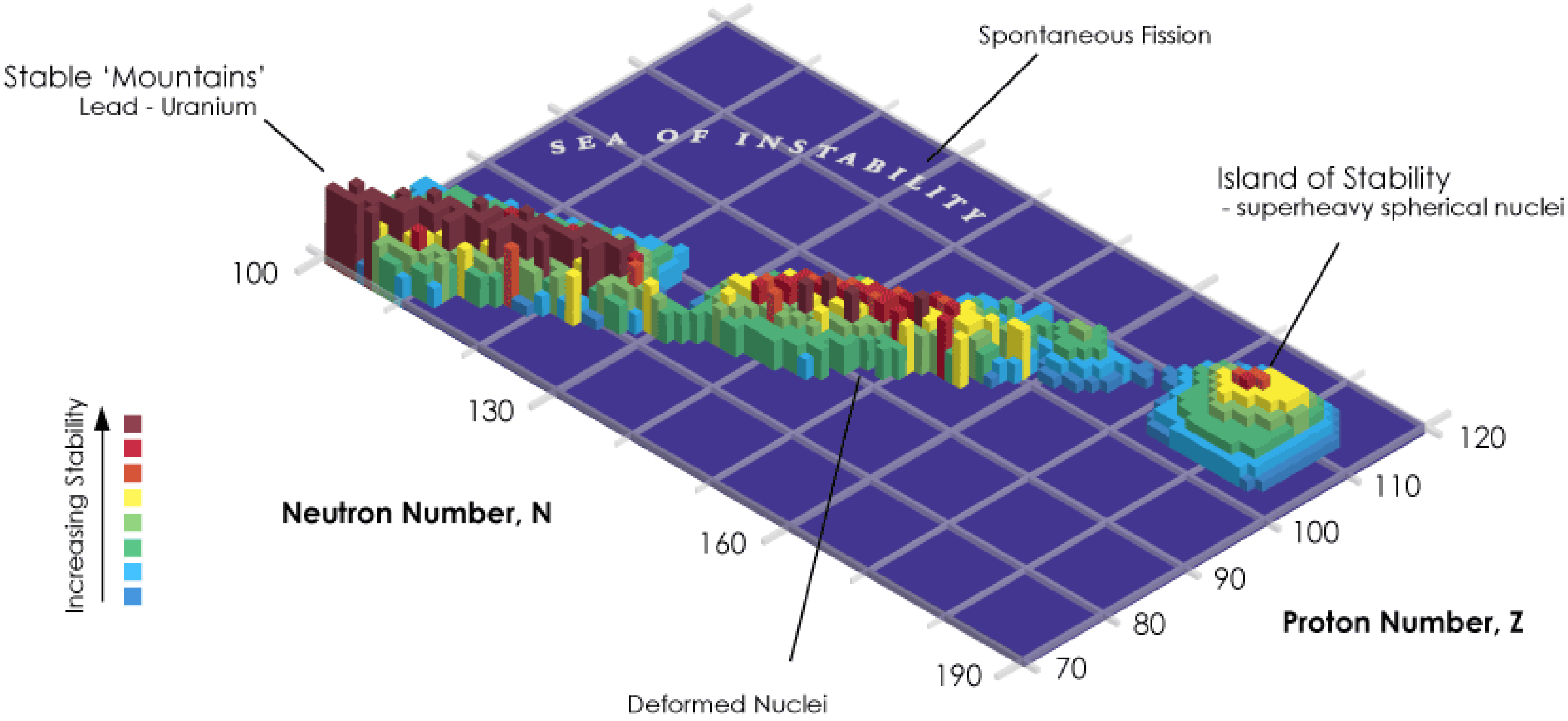
Chemistry - predictions

Projected to be the first member of the 7p series of elements, heaviest member of group 13 in the PT - *eka-thallium.*

In +I state should form monoxide, Nh_2O, and monohalides, NhF, NhCl, NhBr, NhI. The +III state should be less stable than +I state.

Should be the most electronegative in group 13: e.g. in NhTs, the negative charge is expected to be on Nh atom rather than the Ts,

113 – Nihonium (Nh)



3-dimensional rendering of the theoretical island of stability around N=178 and Z=112

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113 – Nihonium (Nh)

Chemistry - experimental

^{284}Nh, ^{285}Nh, and ^{286}Nh stable enough for chemical investigation.

Predicted ΔH_{subl}(Nh) ~ 150 kJ/mol and $\Delta H_{ads,Au}$(Nh) ~ −159 kJ/mol

Preliminary chemical experiments:

Dubna: $^{243}Am(^{48}Ca,3n)^{288}Mc \rightarrow {}^{284}Nh \Rightarrow$ large retention of both elemental Nh and NhOH on Teflon capillaries.

Conclusion: use bromine saturated with boron tribromide as a carrier gas to oxidise Nh to Nh(III) and brominate it, then study oxidation states of nihonium.

114 – Flerovium (Fl)

Official discovery

The now-confirmed discovery of 114 was made in June 1999 when the Dubna team lead by **S. Dmitriev** repeated the reaction in a joint Dubna and LLNL experiment.

$$^{243}\mathrm{Pu}\ (^{48}\mathrm{Ca},3n)\ ^{289}\mathrm{Fl} \xrightarrow{\alpha,\ 2.6\ \mathrm{s}} \textbf{decay chain}$$

Two atoms of element 114 were produced decaying by emission of 9.82 MeV alpha particles with a half life of 2.6 s. Additional isotopes detected as decay products of 116 and 118. Confirmed at LLNL Berkeley and GSI (both in 2009).

Island of stability?

According to theory, Z=114 is the next spherical magic number. In this region, N=184 (or 196) should be the next spherical neutron magic number and hence ^{298}Fl or ^{310}Fl are candidates for the next spherical doubly magic nucleus.

^{298}Fl – centre of a hypothetical ‘island of stability’. **Some $T_{1/2}$ predicted very long, e.g. ^{294}Ds – $T_{1/2}$ ~ 10^{10} y** (similar to Th)
New theory – the next proton magic number not 114 but 122…

Naming

Named after Georgy Flerov - flerovium,

114 – Flerovium (Fl)

Chemistry - predictions

Fl should portray ***eka-lead*** chemical properties – form

- a monoxide, FlO, and dihalides, FlF_2, $FlCl_2$, $FlBr_2$, and FlI_2.
- if +IV state exists, it it should form oxide, FlO_2, and fluoride, FlF_4
- a mixed oxide, Fl_3O_4, analogous to Pb_3O_4 may also exist.

Some studies also suggest that the chemical behaviour of flerovium might in fact be closer to that of the noble gas radon, than to that of lead.

Main isotopes of flerovium

Isotope	Half-life	Decay mode	Product
^{290}Fl	19 s?	EC	^{290}Nh
		α	^{286}Cn
^{289}Fl	**1.9 s**	**α**	**^{285}Cn**
^{288}Fl	0.64 s	α	^{284}Cn
^{287}Fl	0.54 s	α	^{283}Cn
		EC?	^{287}Nh
^{286}Fl	0.17 s	40% α	^{282}Cn
		60% SF	
^{285}Fl	0.15 s	α	^{281}Cn
^{284}Fl	2 ms	SF	

114 – Flerovium (Fl)

Chemistry - experimental

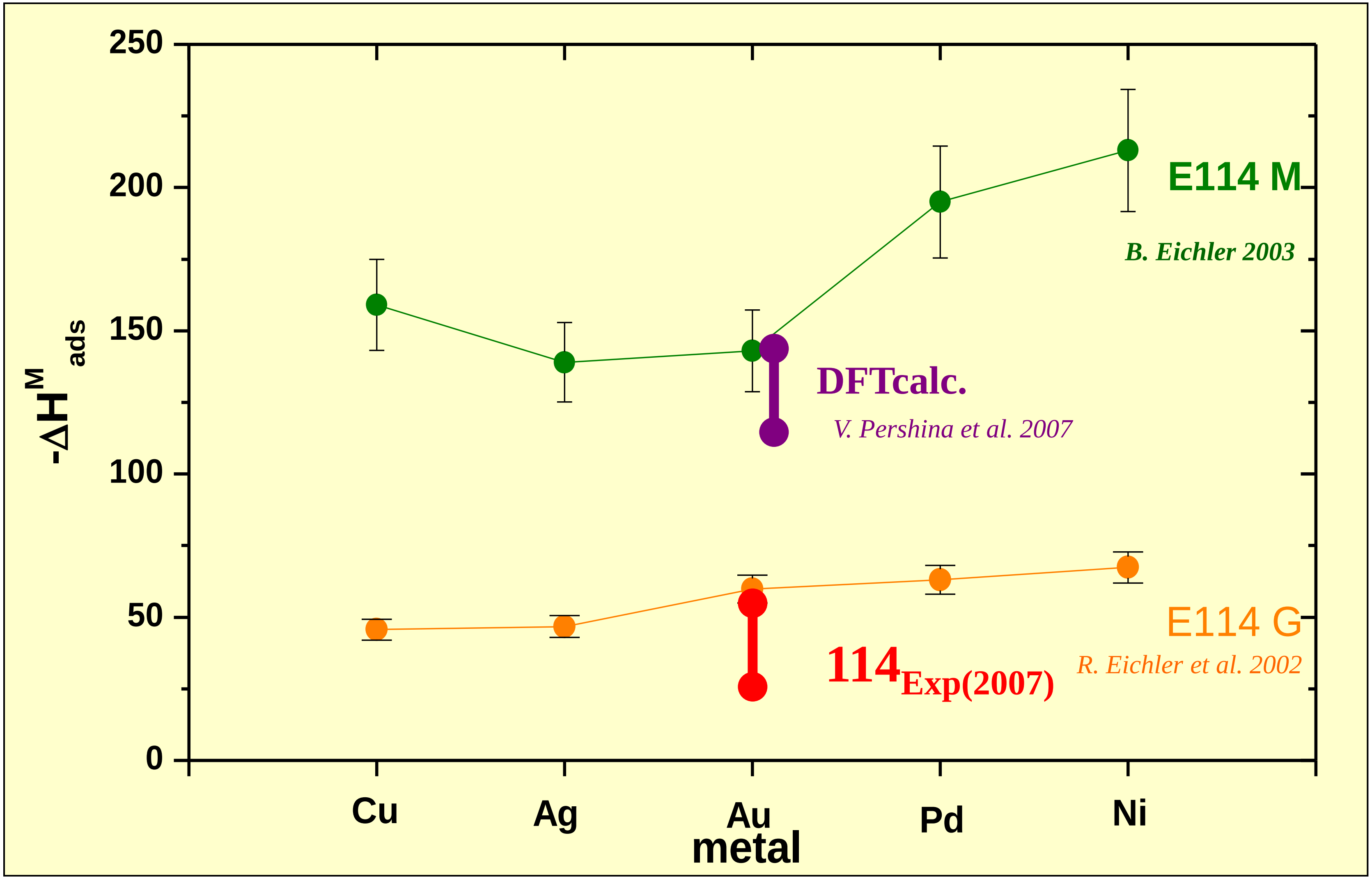
The heaviest element studied till today.
Performed by FLNR – PSI collaboration together with the Cn study.
Isotope production: ^{242}Pu(^{48}Ca,3n)^{287}Fl and ^{244}Pu(^{48}Ca,4n)^{288}Fl (both decay to Cn that has been studied primarily). 4 Fl atoms detected.
Sugestion: noble-gas-like interaction of flerovium with gold.

Further experiments - volatility of flerovium comparable to mercury, astatine, or copernicium.
Sugestion: new category of **"volatile metals"** – Kratz may be gaseous at standard temperature and pressure, fall between normal metals and noble gases in terms of adsorption properties

Conclusion: Flerovium is the least reactive element in the group, but still a metal. However, the question of whether flerovium is a metal or a noble gas is still open.

Results

Dubna 2007



115 – Moscovium (Mc)

Official discovery

First synthesised in 2003 by joint LLNL-JINR team headed by Yuri Oganessian at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia.

$$^{243}\mathrm{Am}\,(^{48}\mathrm{Ca},3\text{-}4n)\,^{288,287}\mathrm{Mc} \rightarrow {}^{284,283}\mathrm{Nh} \xrightarrow{\alpha,} \text{decay chain}$$

Then-observed life-times about 100 milliseconds.

Naming

Eka-bismuth. Suggested names included *langevinium*, after Paul Langevin. Moscovium referrs to the Moscow Oblast where Dubna is located.

Main isotopes of moscovium

Isotope	Half-life	Decay mode	Product
^{290}Mc	0.8 s	α	^{286}Nh
^{289}Mc	0.3 s	α	^{285}Nh
^{288}Mc	0.2 s	α	^{284}Nh
^{287}Mc	40 ms	α	^{283}Nh

115 – Moscovium (Mc)

Chemistry - predictions

Member of group 15, the pnictogens, below nitrogen, phosphorus, arsenic, antimony, and bismuth – ***eka-bismuth***.

Relativistic stabilization of the 7s and $7p_{1/2}$ orbitals (inert pair effect) should result in some unique properties of moscovium(I) – behaving more like thallium(I) than bismuth(I).

If flerovium displays closed-shell or noble gas-like properties, moscovium will likely be typically monovalent perhaps giving moscovium some alkali metal character.

However, the Mc^{3+} cation would behave like its true lighter homolog Bi^{3+}.

The +5 state should be impossible due to the stabilization of 7s electrons – moscovium may be considered to have only three valence electrons.

Moscovium would be quite a reactive metal,

Chemistry - experimental

Not performed, yet, however the half-lives of ^{288}Mc, ^{289}Mc, and ^{290}Mc are long enough for chemical investigations with current methods.

116 – Livermorium (Lv)

The heaviest member of group 16 although its position as the heavier homologue to polonium has not been confirmed, yet, by chemical studies. First detected in 2000

$$^{248}\mathrm{Cm}\ (^{48}\mathrm{Ca},3n)\ ^{293}\mathrm{Lv} \xrightarrow{\alpha,\ 60\ \mathrm{ms}} {}^{289}\mathrm{Fl} \xrightarrow{\alpha} \text{decay chain}$$

since then about 30 atoms of Lv have been produced, either directly or as a decay product of Og.

Naming

Historically known as eka-polonium. The name livermorium and the symbol Lv adopted on May 31, 2012. The name recognises the Lawrence Livermore National Laboratory, within the city of Livermore, CA (USA), which collaborated with JINR on the discovery. The city in turn is named after the American rancher Robert Livermore, a naturalized Mexican citizen of English birth.

116 – Livermorium (Lv)

Known isotopes

Isotope	Half-life	Decay mode	Energy (MeV)	Daughter
^{293}Lv	60 ms	α	9.95	^{286}Nh
^{292}Lv	12 ms	α	10.31	^{285}Nh
^{291}Lv	18 ms	α	10.46	^{284}Nh
^{290}Lv	8 ms	α	10.59	^{283}Nh

Chemistry - predictions

Member of group 16 – chalcogens – valence configuration predicted as $7s^2 7p^4$.

Continue the trends – melting point higher but boiling point lower than Po.

Denser metal than Po – around 12.9 g/cm^3.

The mass of the electron of Lv$^+$ expected to be 1.86 times that of a stationary electron, due to relativistic effects.

Most stable oxidation state +2, +4 unstable (only in e.g. LvF_4), +6 should not exist, –2 very unstable – chemistry cationic only.

Livermorane (LvH_2) – heaviest homologue of water. Hydride-like but still covalent.

Chemistry - experimental

No experiments, yet, no isotopes stable enough for current methods. For the results with lighter homologues see moscovium.

117 – Tennessine (Ts)

The heaviest member of halogen family – ***eka-astatine*** – although its position as the heavier homologue to polonium has not been confirmed, yet. May be located in the island of stability. Six atoms detected by a joint JINR–ORNL–Vanderbilt –LLNL collaboration at Dubna, Moscow Oblast, Russia, in 2009–10.

$$^{249}\mathrm{Bk}\,(^{48}\mathrm{Ca},3\text{-}4n)\;^{293,294}\mathrm{Ts}\;\xrightarrow{\alpha,}\;\textbf{decay chain}$$

Half-lives of ^{293}Ts or ^{294}Ts equal to 20 ms or 50 ms, respectively.

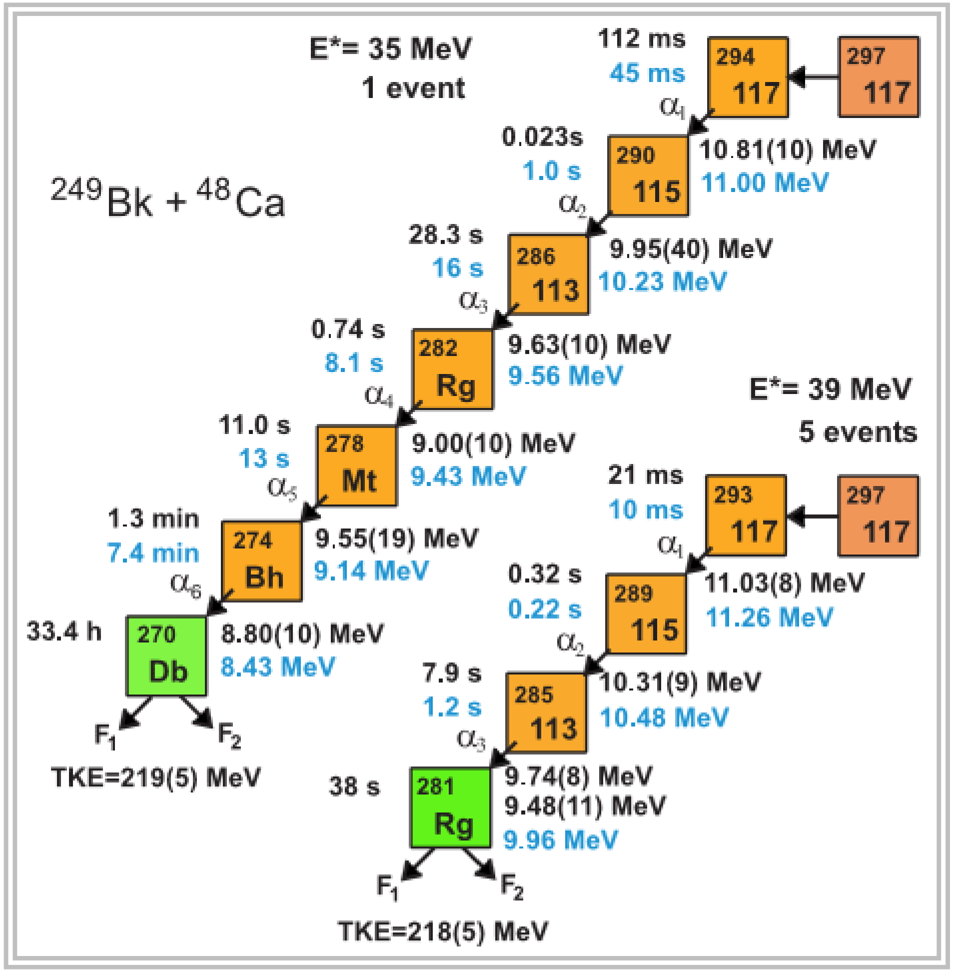
Naming

Historically known as ***eka-astatine***. The name *tennessine*, with a symbol of *Ts*, after "the region of Tennessee“, accepted by the IUPAC in November 2016.
–*ine* to mimic lighter halogens.

Chemistry

Expected to behave similarly to the halogens in many respects, however, going down group 17, the metallicity increases; hence, an extrapolation based on periodic trends would predict tennessine to be a rather volatile post-transition metal.
Aside from the unstable −1 state, three more oxidation states are predicted; +5, +3, and +1 (especially stable).
No experimental chemistry possible today.

117 – Tenessine (Ts)



Decay chain of the isotopes of tennessine produced in the original experiment. The figures near the arrows describe experimental (**black**) and theoretical (**blue**) values for the half-life and energy of each decay.

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118 – Oganesson (Og)

Official discovery

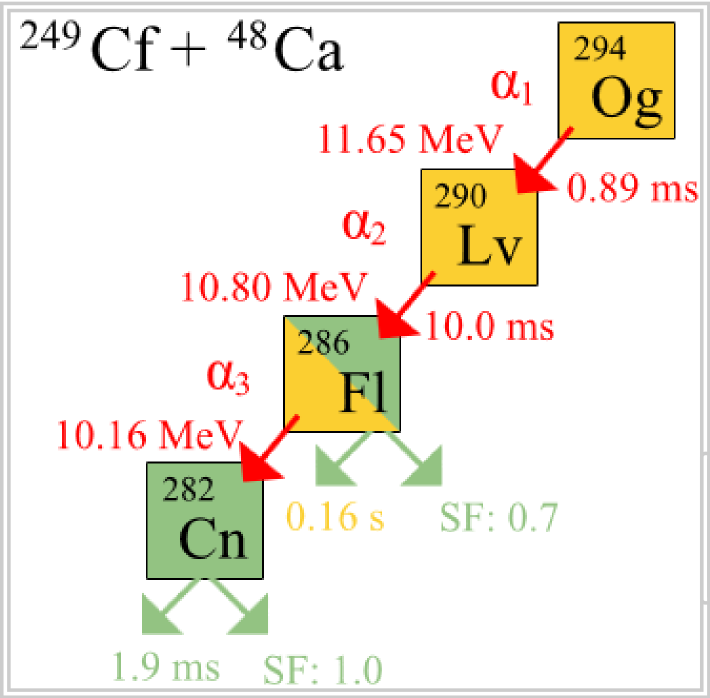
Claimed (together with livermorium) for the first time by LBNL (Lawrence Berkeley National Laboratory) in 1999 in reaction

$$^{208}\mathrm{Pb}\ (^{86}\mathrm{Kr},\ n)\ ^{293}\mathrm{Og}$$

Retracted next year – data found fabricated….

Officially discovered by a collaboration of JINR Dubna and LLNL led by Yuri Oganessian. Experiments performed in 2002 – 2006, three atoms of ^{294}Og seen

$$^{249}\mathrm{Cf}\ (^{48}\mathrm{Ca},\ 3n)\ ^{294}\mathrm{Og} \xrightarrow{\alpha,\ 0.89\ \mathrm{ms}} \textbf{decay chain}$$



Supporting experiments on synthesis and study of the before unknown ^{290}Lv daughter followed till the recognition in 2015 and naming in 2016.

Radioactive decay chain of ^{294}Og.
(The fraction of spontaneous fission in green.)

118 – Oganesson (Og)

Naming

Historically known as eka-radon.
Named Oganesson (Og) in 2016 after Yuri Oganessian.

Chemistry - predictions

Member of group 18 – noble gases – valence configuration predicted as $7s^2 7p^6$.
Expected to be (slightly) more reactive than radon.
Expected boiling point 320–380 K – not a gas under standard conditions…
+2 and +4 predicted to exist in OgF_2 and OgF_4, +6 less stable.

Chemistry - experimental

No experiments, yet, no isotopes stable enough for the current methods.

Known isotopes

Isotope	Half-life	Decay mode	Energy (MeV)	Daughter
^{294}Og	0.7 ms	α	11.65	^{290}Lv

$Z = 119 – 120$

Synthesis

1. **^{n}Es (^{48}Ca,*x*n) $^{(n-x)}$119** **Problem:** **Availability and half-lives of target nuclides**

   ^{n}Fm (^{48}Ca,*x*n) $^{(n-x)}$120

2. **New heavier projectiles on actinide targets**
   - **$_{22}$Ti: ^{249}Bk (^{50}Ti,*x*n) $^{299-x}$119, ^{249}Cf (^{50}Ti,*x*n) $^{299-x}$120 – JINR Dubna**
   - **$_{23}$V: ^{248}Cm (^{50}V,*x*n) $^{298-x}$119 – RIKEN**

3. **Cold fusion revisited** **Problem:** **Extremely low cross sections**

Chemistry – predictions

Members of groups 1 and 2:

- 119 – alkali metal….
- 120 – alkaline earth metal….

Periodic table of the elements

Outlook / Extended PTE

		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 113	114 Fl	115 115	116 Lv	117 117	118 118
8	119 119	120 120	121 121	154 154	155 155	156 156	157 157	158 158	159 159	160 160	161 161	162 162	163 163	164 164	165 165	166 166	167 167	168 168

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

SuperActinides 122 121 - - - - - - 153 153 (32 g/f-elements – 18x 5g + 14x 6f)

TransActinides 104 Rf - 121 121

TransSuperActinides 154 154 - 168 168