www.superheavies.de
c.e.duellmann@gsi.de

Superheavy element research at GSI on the way to FAIR

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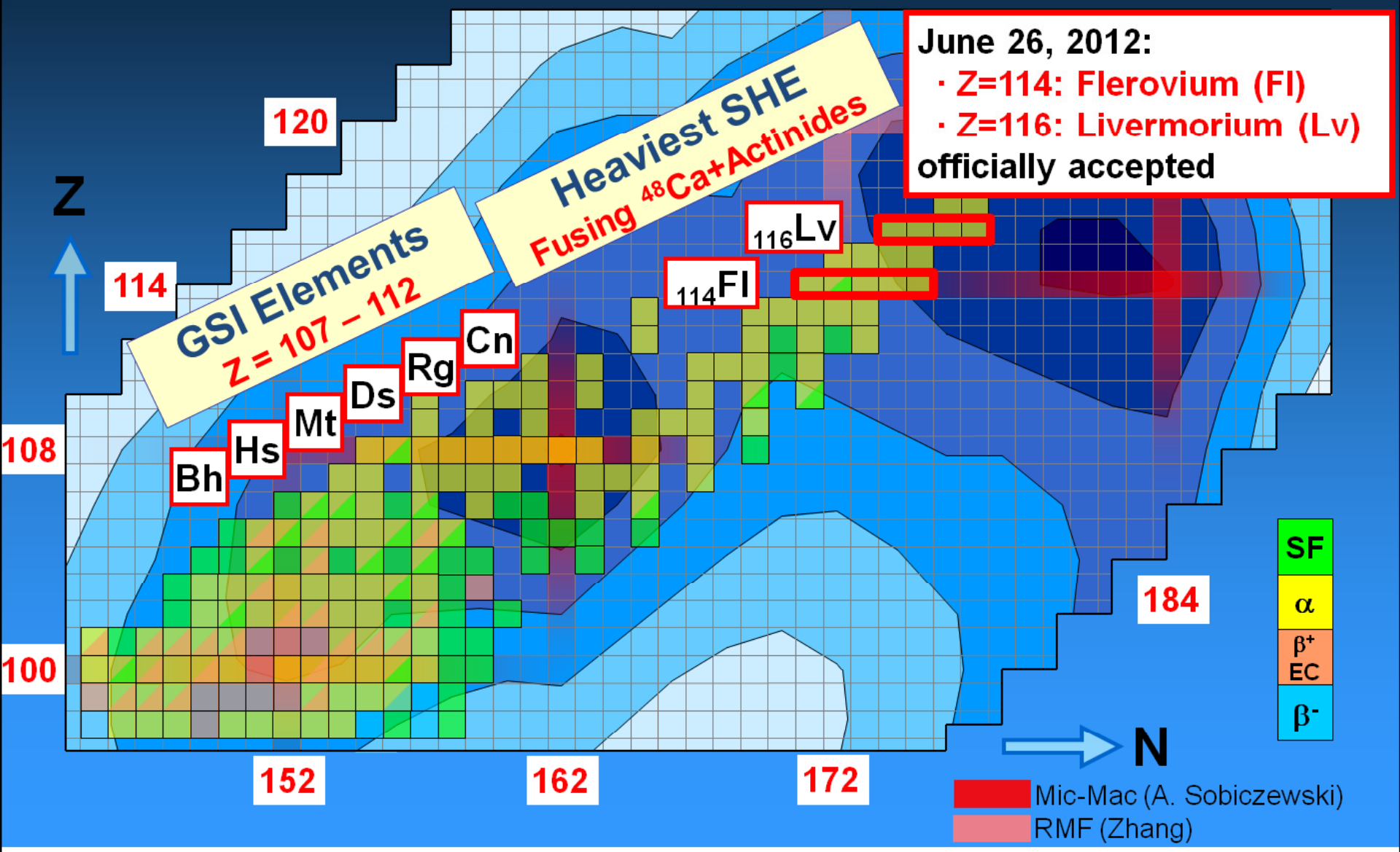
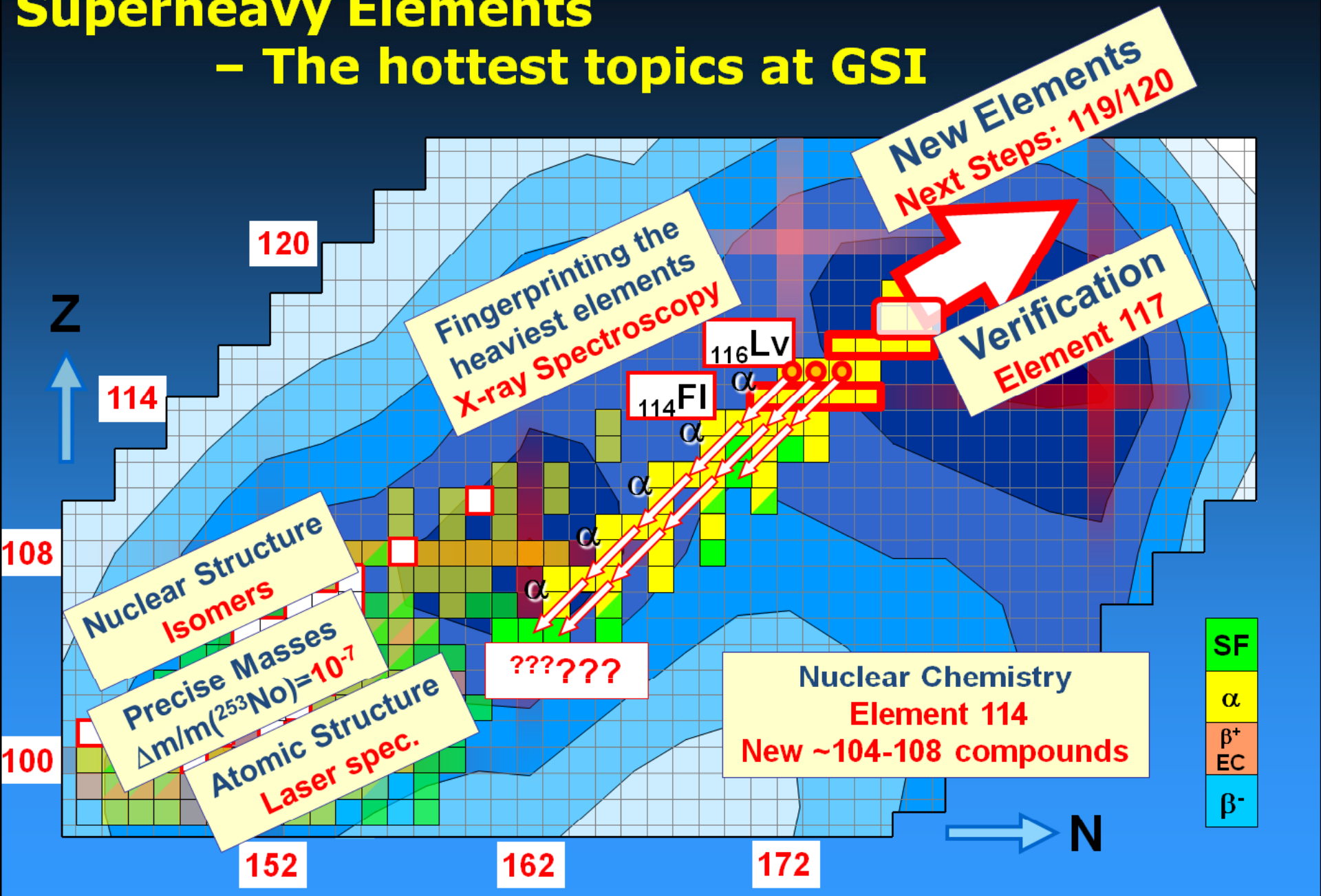
PRISMA Cluster of Excellence & Institute of Nuclear Chemistry, **Johannes Gutenberg University Mainz**
SHE Chemistry, **GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt**
SHE Chemistry, **Helmholtz Institute Mainz**

NUSTAR Week
September 23 – 26, 2014; Valencia, Spain

Superheavy Elements (SHE) – Current Status

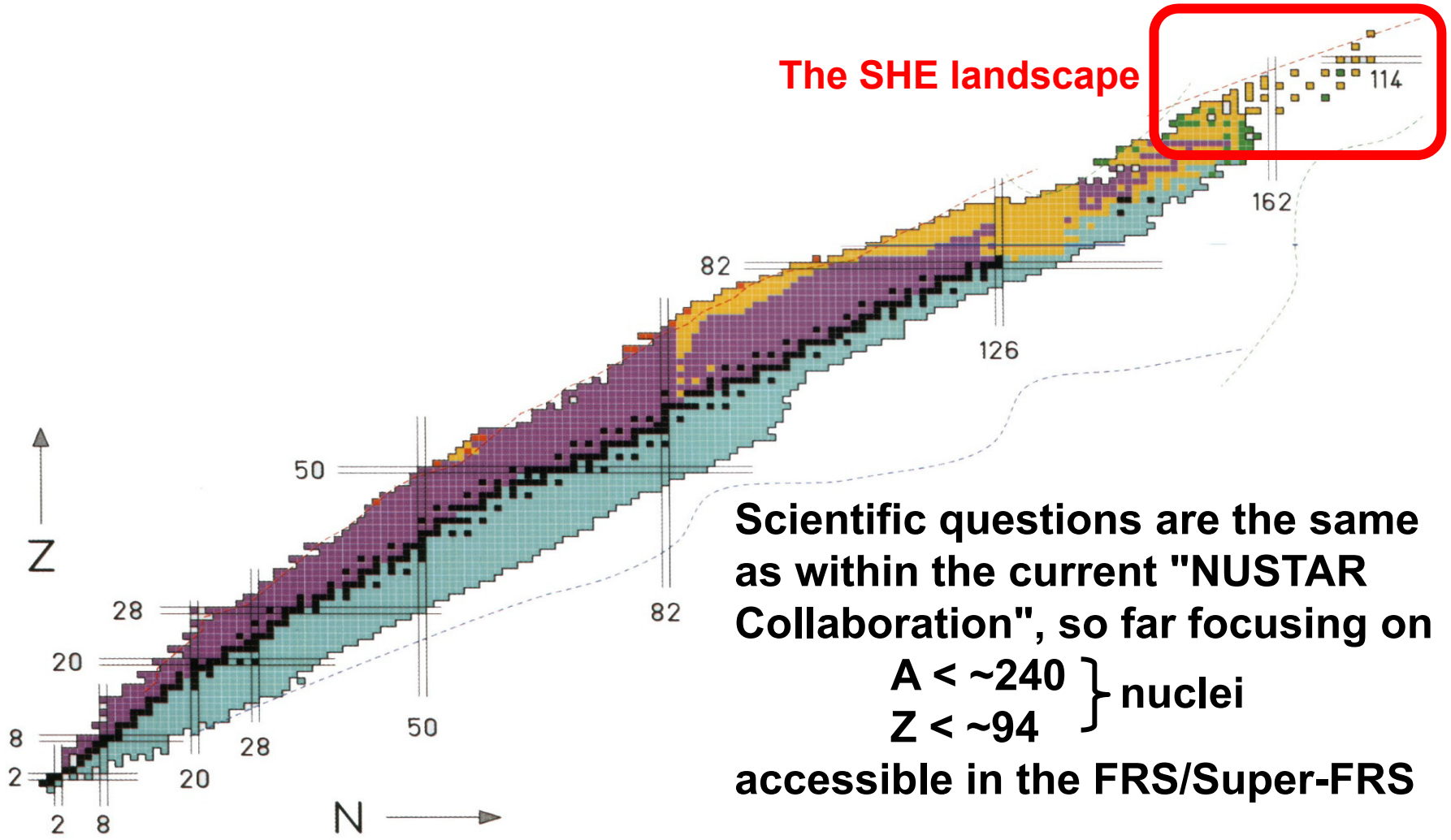


Superheavy Elements – The hottest topics at GSI



Scientific questions in SHE research

- superheavy elements (SHE) – atomic nuclei at the extremes of highest Z, N, and A
- element synthesis in stars: where does the astrophysical r-process end?

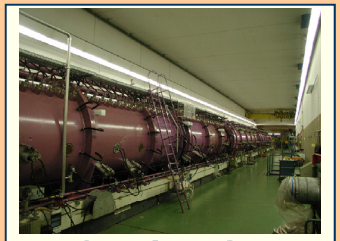


Scientific questions are the same as within the current "NUSTAR Collaboration", so far focusing on

A < ~240
Z < ~94
} nuclei

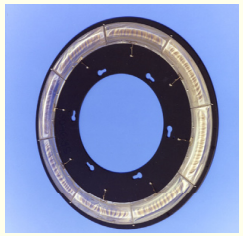
accessible in the FRS/Super-FRS

Unique Combination for SHE Studies

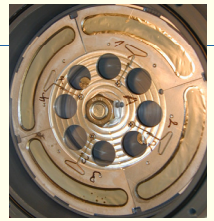


ECR/PIG + UNILAC

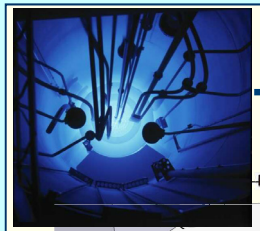
Beam



Stable targets



Actinide targets

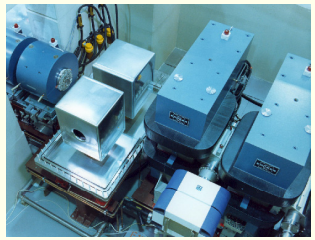


TRIGA-

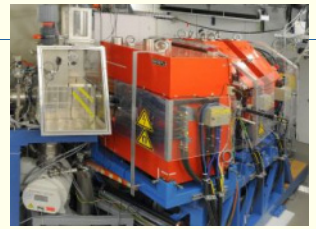
-LASER

-TRAP

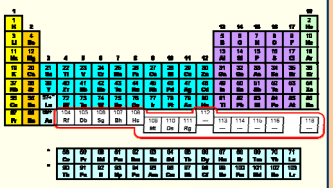
Radiochem. labs



SHIP

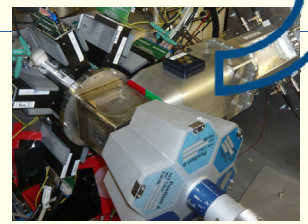


TASCA

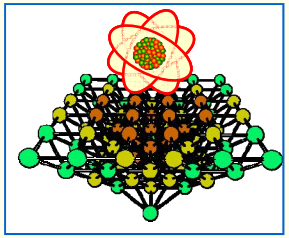


Chemistry

SHIPTRAP



TASISpec



Chemical theory

The *TASCA* Collaboration

LBNL/UCB Berkeley (USA)
LLNL Livermore (USA)
Vanderbilt U (USA)
ORNL Oak Ridge (USA)
U Liverpool (UK)
U Surrey (UK)
U Lund (Sweden)
JAEA Tokai (Japan)

U Jyväskylä (Finland)
U Oslo (Norway)
Chalmers U Gothenburg (Sweden)
PSI Villigen/U Berne (Switzerland)
ITE Warschau (Poland)
SINP Kolkata (India)
IMP Lanzhou (China)
ANU Canberra (Australia)

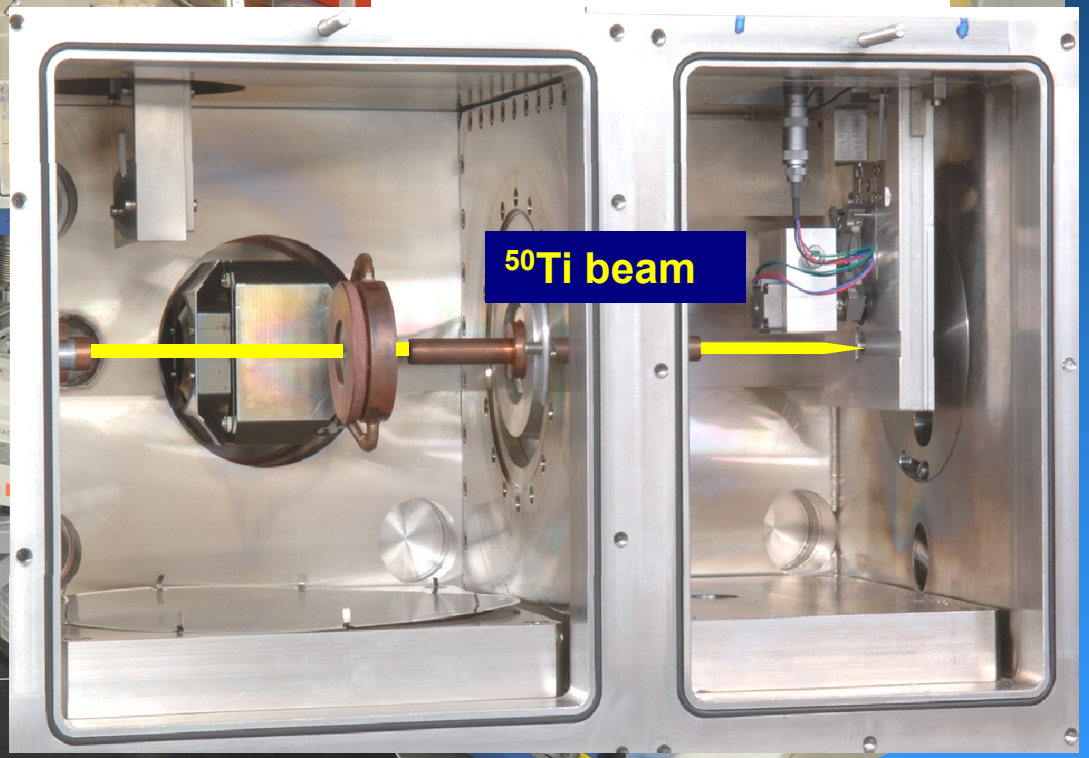
TransActinide Separator and Chemistry Apparatus

www.gsi.de/tasca

GSI

TransActinide Separator and Chemistry Apparatus

TASCA



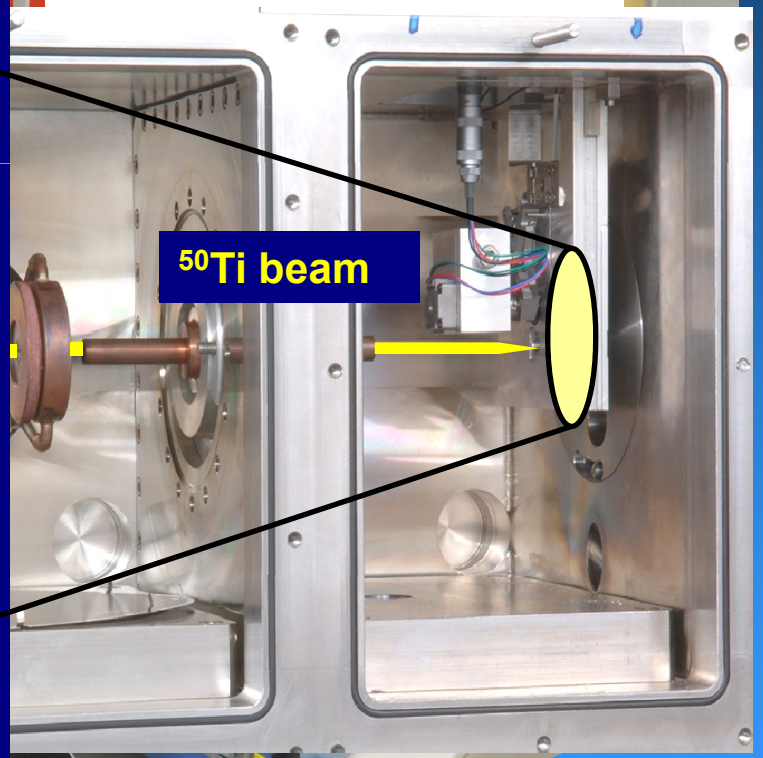
www.gsi.de/tasca

GSI

TransActinide Separator and Chemistry Apparatus

TASCA

Target Chamber
side view

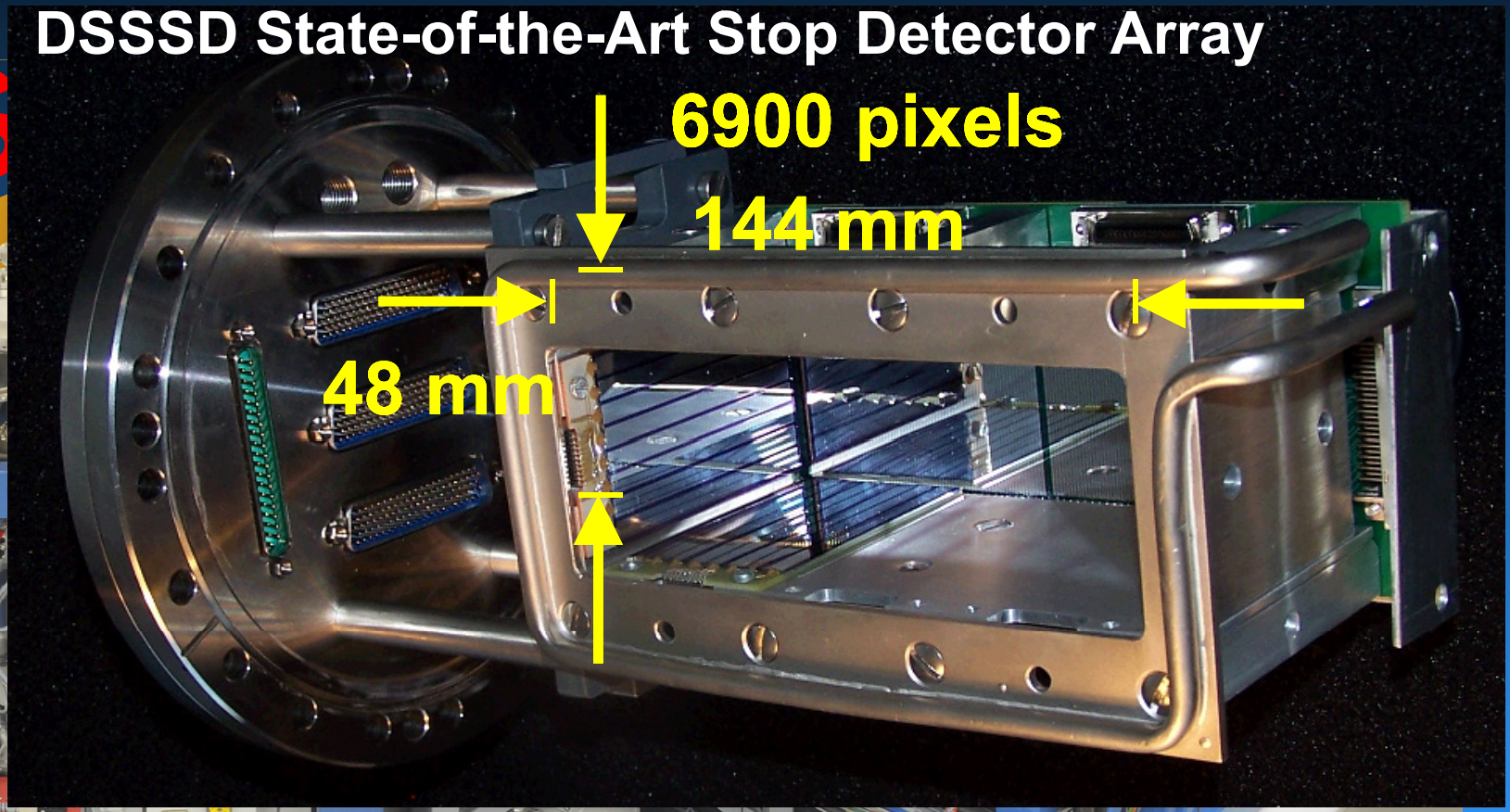


www.gsi.de/tasca

GSI

TransActinide Separator and Chemistry Apparatus

TASCA

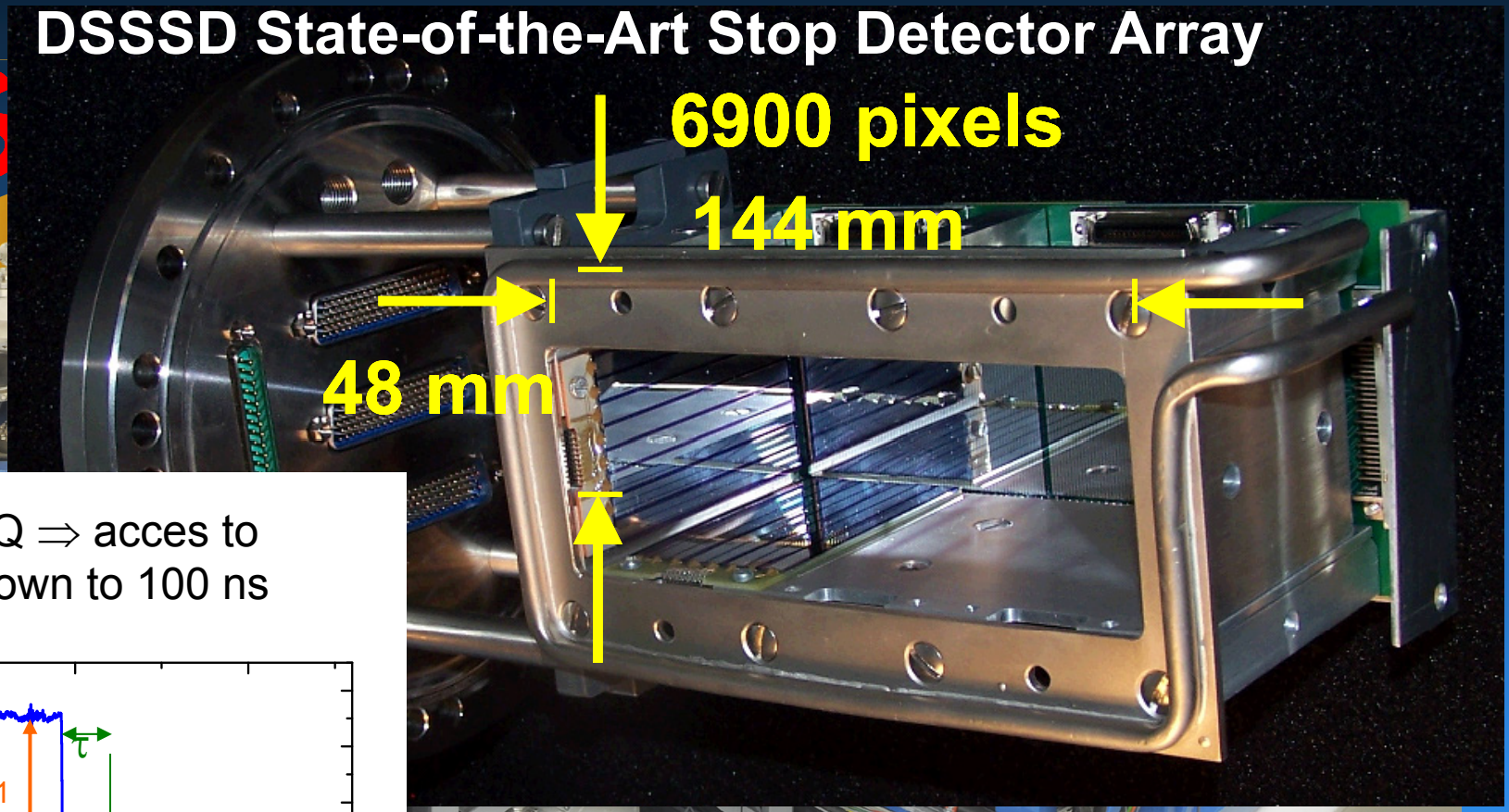


www.gsi.de/tasca

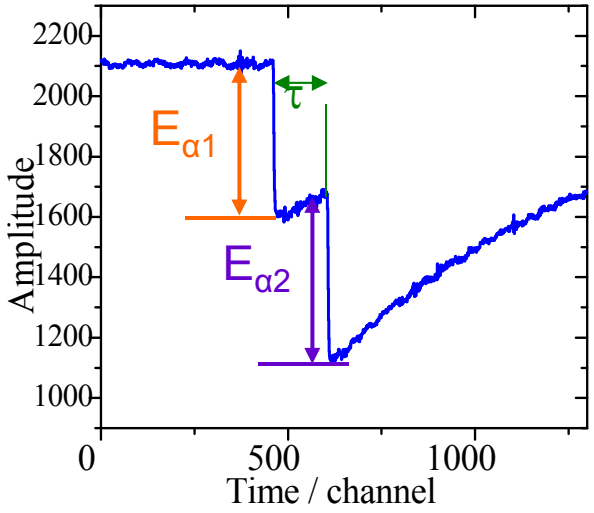
GSI

TransActinide Separator and Chemistry Apparatus

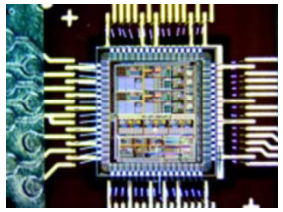
DSSSD State-of-the-Art Stop Detector Array



Digital DAQ ⇒ acces to lifetimes down to 100 ns



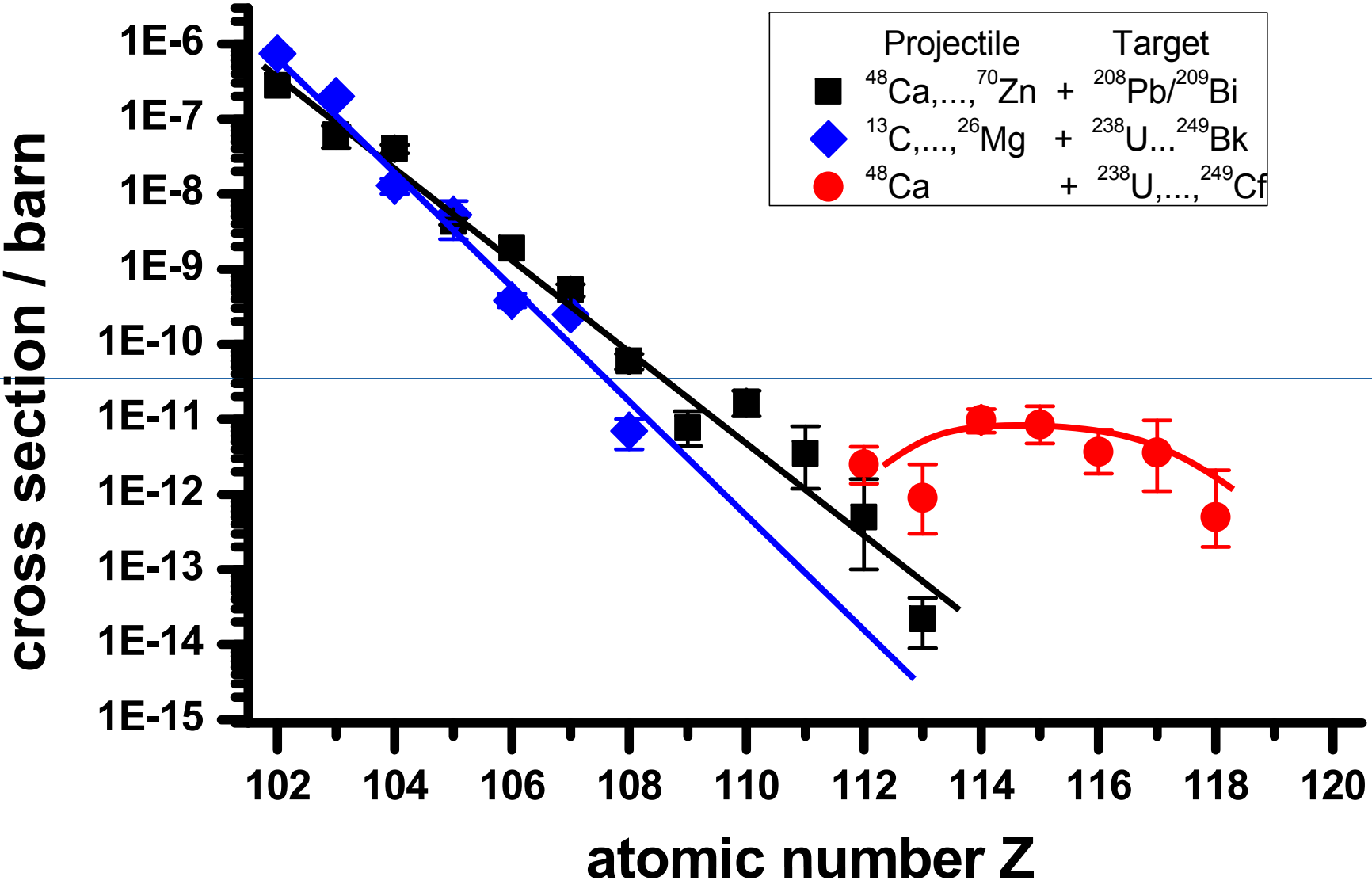
Digital DAQ from GSI EE – Examples



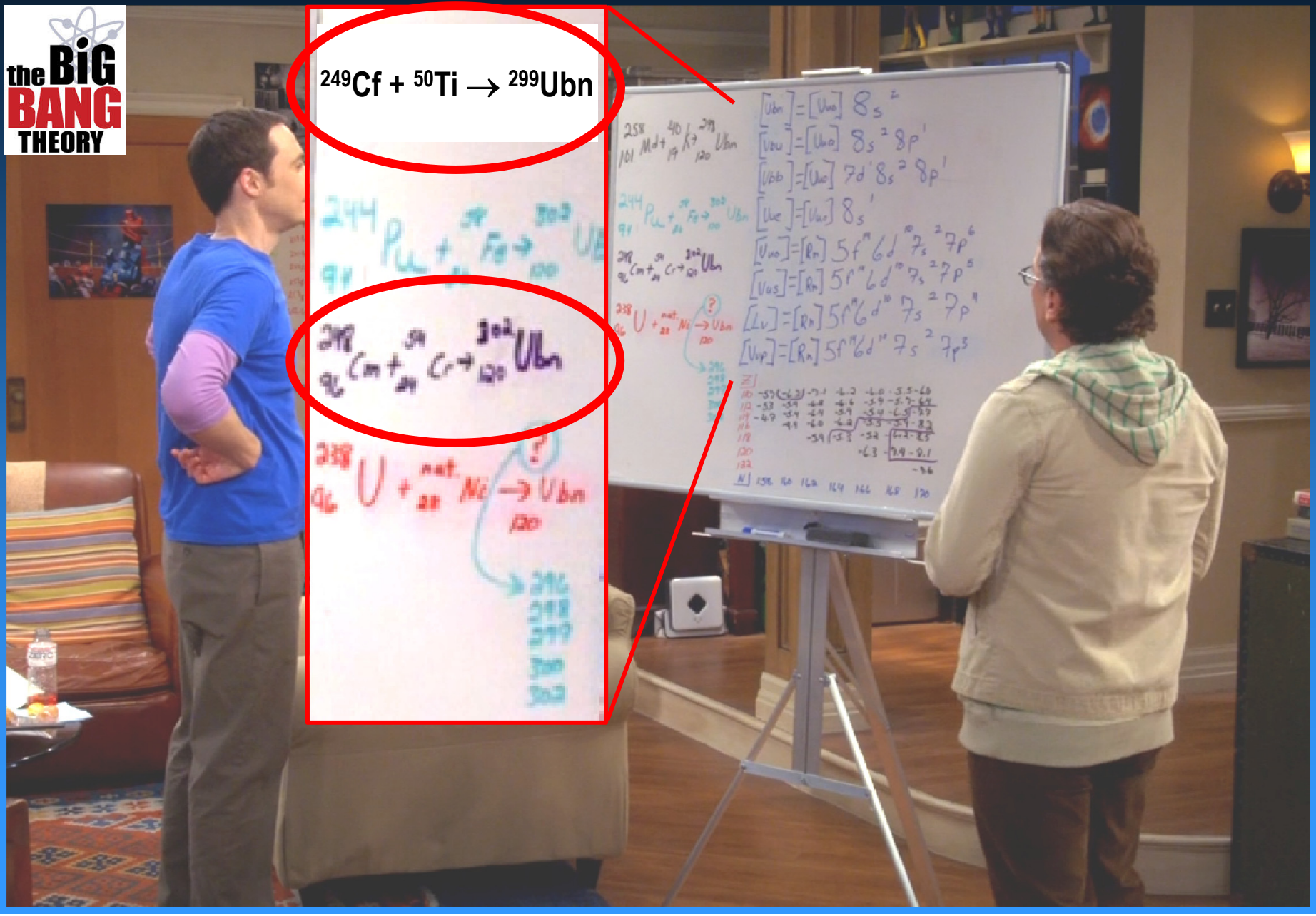
ASIC for PANDA Front End ELectronics (APFEL) Chip

- -development for panda
- -option for *TASCA* DAQ

Synthesis of superheavy elements



How to synthesize element 120?



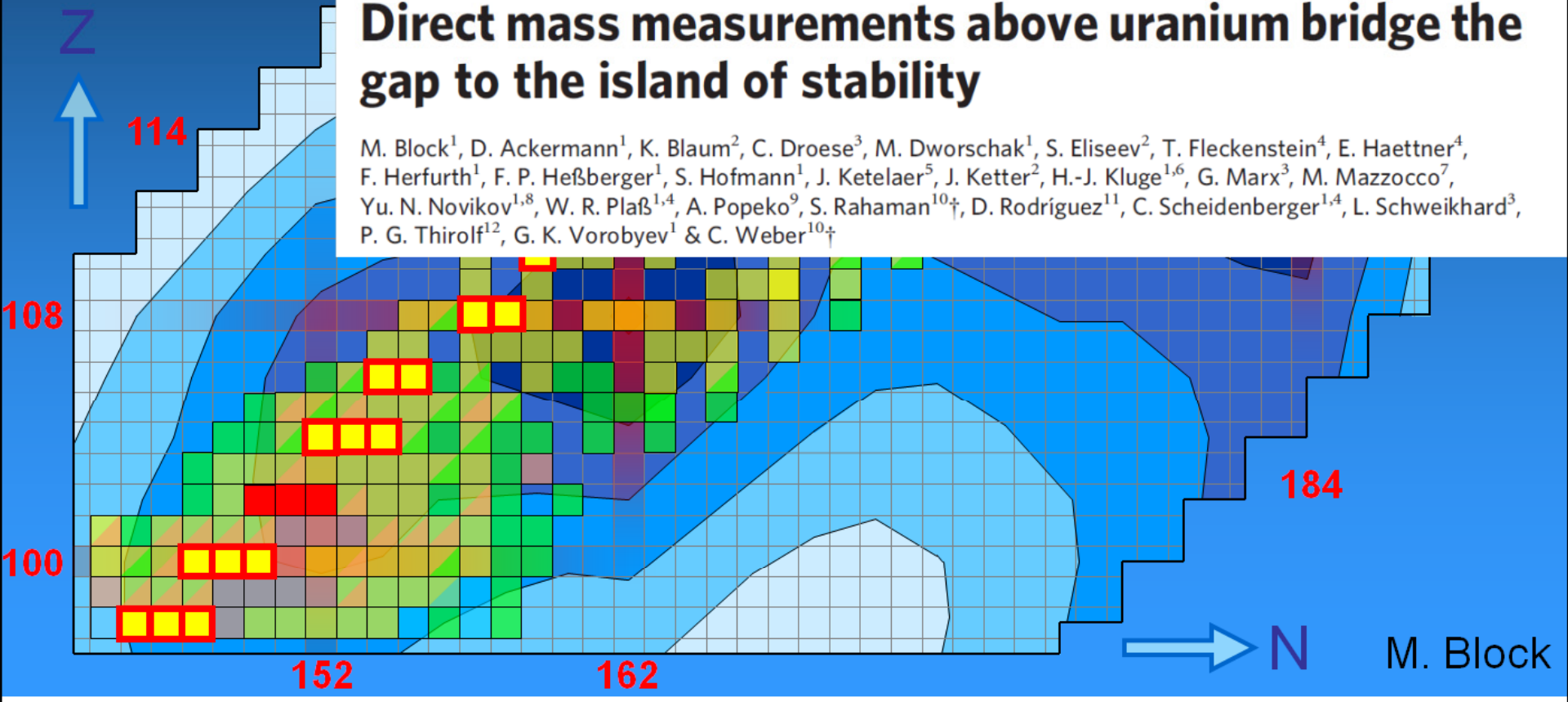
High precision mass measurements: Impact of $^{252-254}$No data

Vol 463 | 11 February 2010 | doi:10.1038/nature08774 nature

LETTERS

Direct mass measurements above uranium bridge the gap to the island of stability

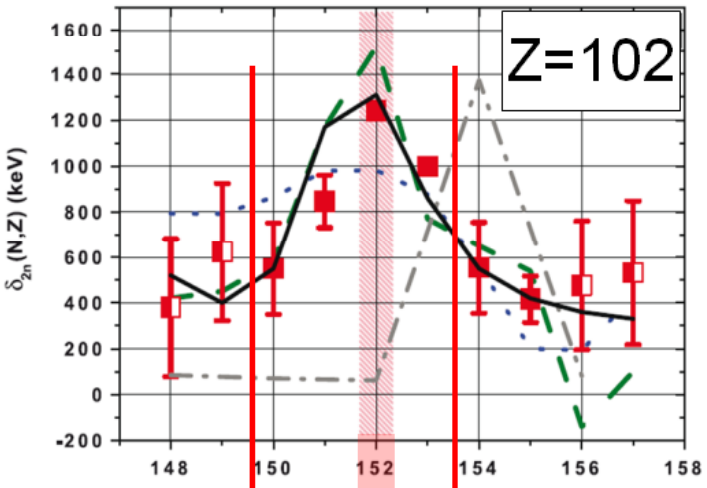
M. Block[1], D. Ackermann[1], K. Blaum[2], C. Droese[3], M. Dworschak[1], S. Eliseev[2], T. Fleckenstein[4], E. Haettner[4], F. Herfurth[1], F. P. Heßberger[1], S. Hofmann[1], J. Ketelaer[5], J. Ketter[2], H.-J. Kluge[1,6], G. Marx[3], M. Mazzocco[7], Yu. N. Novikov[1,8], W. R. Plaß[1,4], A. Popeko[9], S. Rahaman[10]†, D. Rodríguez[11], C. Scheidenberger[1,4], L. Schweikhard[3], P. G. Thirolf[12], G. K. Vorobyev[1] & C. Weber[10]†



High precision mass measurements:

Direct mapping of a nuclear shell closure in heaviest elements

Science
337 (2012) 1207



- Experimental
- Muntian (mic-mac) Z=114 N=184
- Möller FRDM Z=114 N=184
- TW-99 Z=120 N=172
- SkM* Z=126 N=184

Probing N=152 at lower Z using TRIGA-TRAP @ JG|U / PRISMA

First data on ^{244}Pu, ^{249}Cf

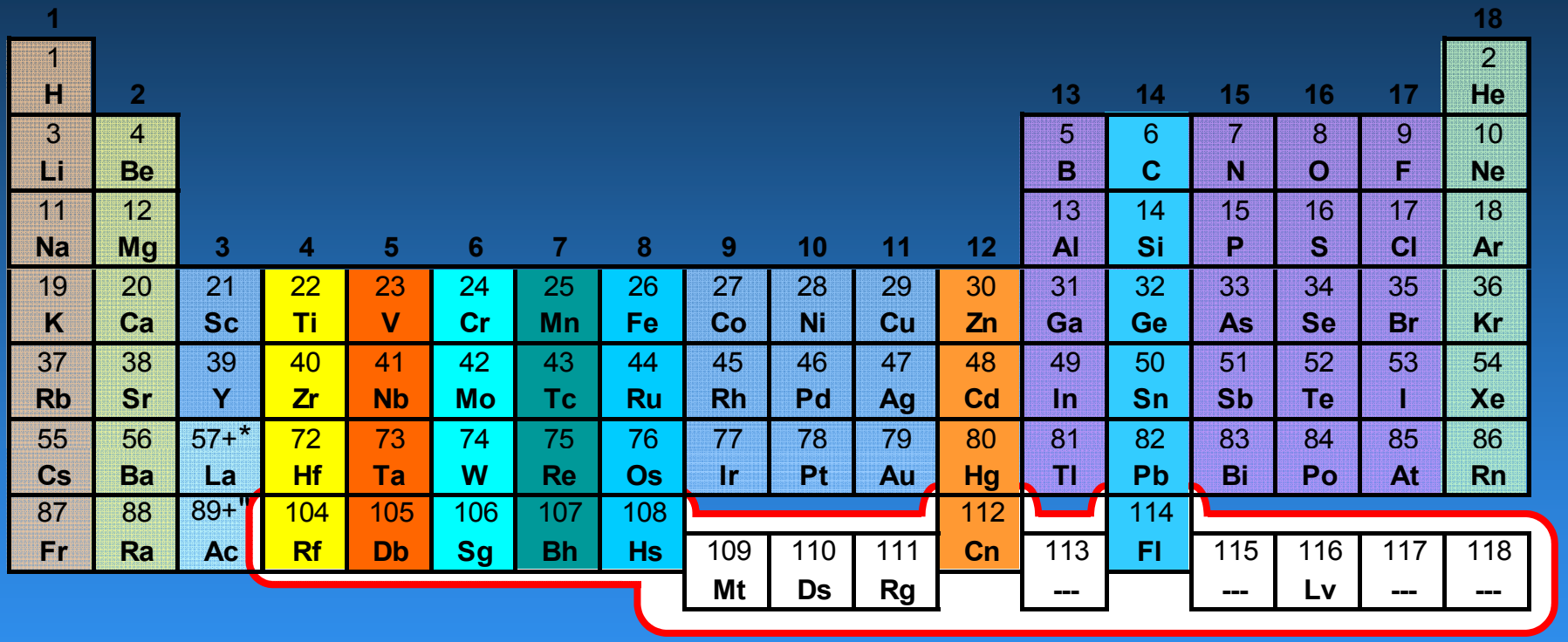
M. Eibach et al., PRC 89 (2014) 064318

Cf 249
350.6 a
α 5.812; 5.758..
sf; γ 388...; g

100
152
184
N

M. Block

SHE Chemical studies



*	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
"	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

A. Türler + V. Pershina, Chem. Rev. 113 (2013) 1237
M. Schädel, Angew. Chem. Int. Ed., 2006

SHE Chemical studies

Gas phase:

Gr 4: $RfCl_4$, $RfBr_4$, $RfOCl_2$

Gr 5: $DbCl_5$, $DbOCl_3$, $DbBr_5$

Gr 6: SgO_2Cl_2; $SgO_2(OH)_2$

Gr 7: BhO_3Cl

Gr 8: HsO_4, $Na_2HsO_4(OH)_2$

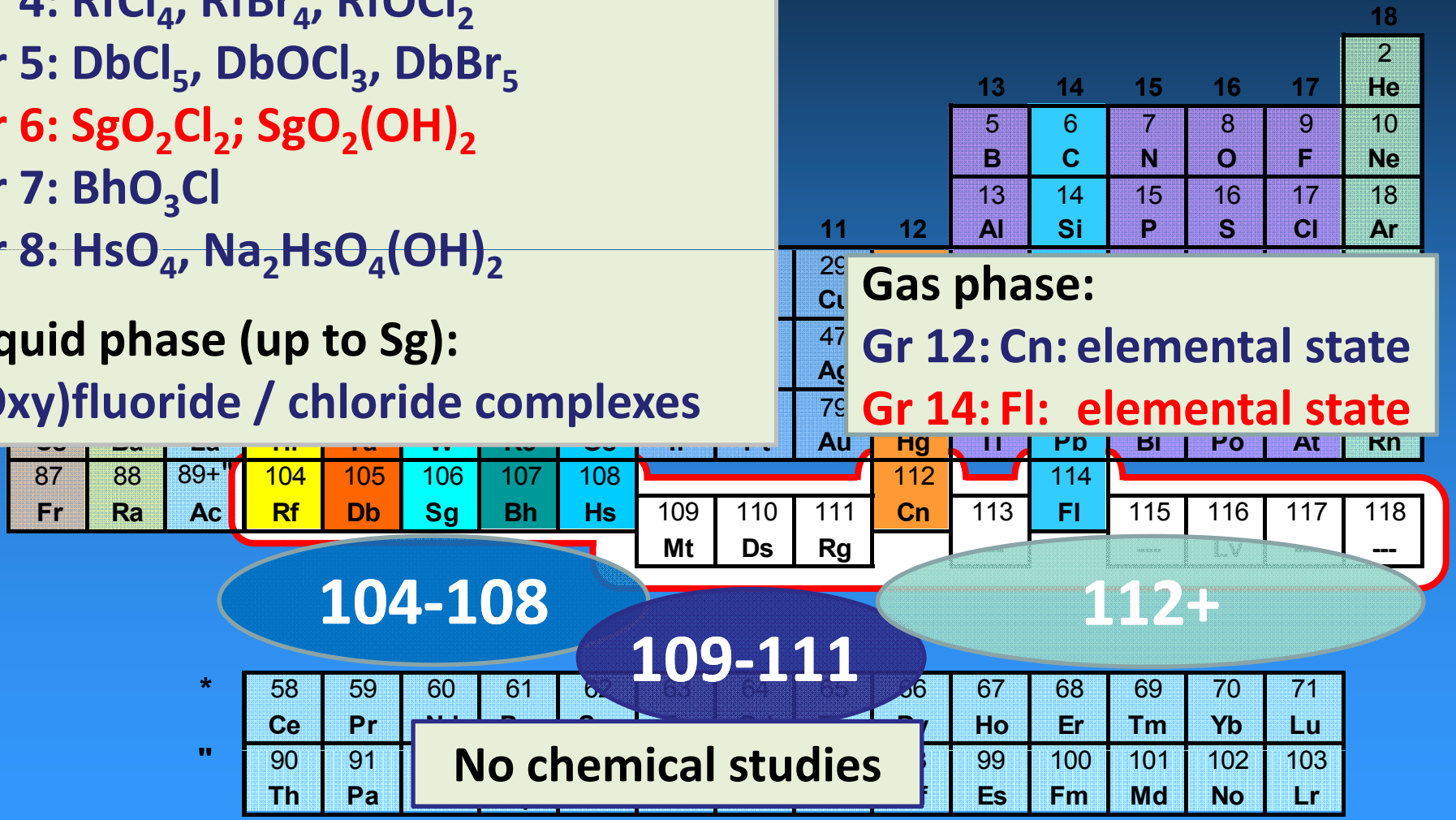
Liquid phase (up to Sg):

(Oxy)fluoride / chloride complexes

Gas phase:

Gr 12: Cn: elemental state

Gr 14: Fl: elemental state

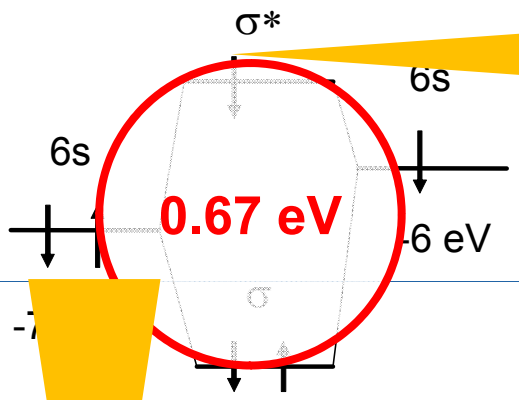


A. Türler + V. Pershina, Chem. Rev. 113 (2013) 1237
M. Schädel, Angew. Chem. Int. Ed., 2006

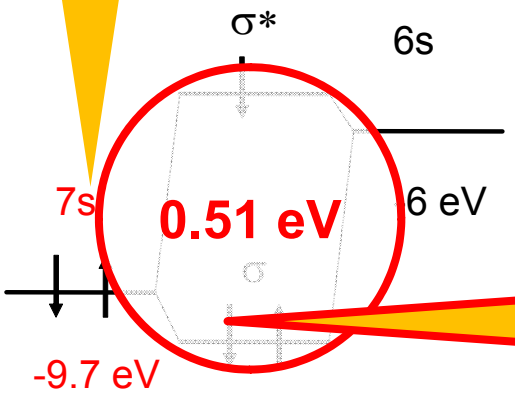
M-Au Bonding (Dimer)

Group 12

Hg-Au

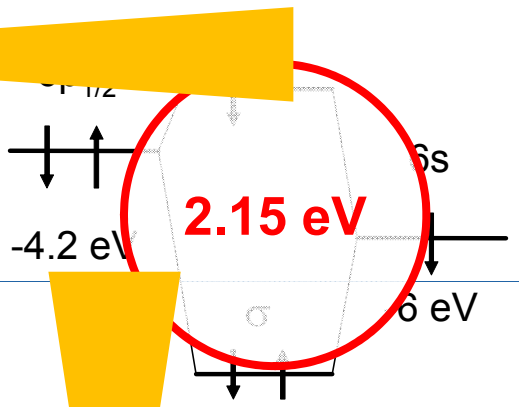


Cn-Au

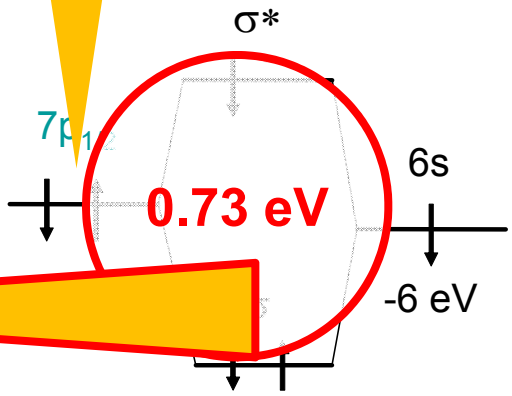


Group 14

Pb-Au

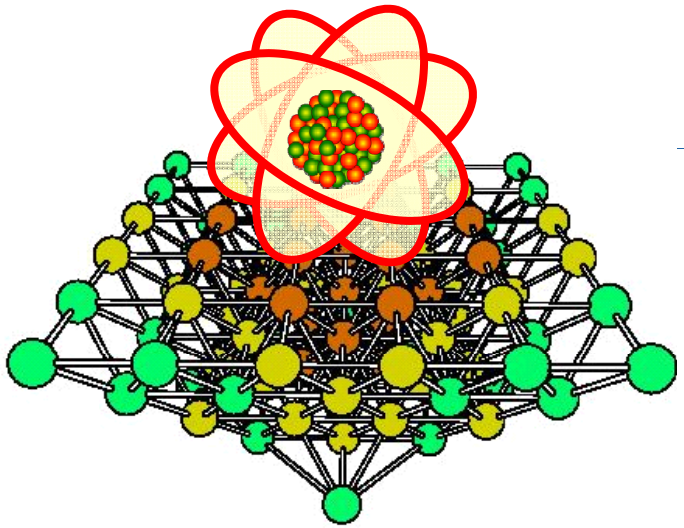


Fl-Au



Fl-Au bond: stronger than Cn-Au

M on Au_n cluster



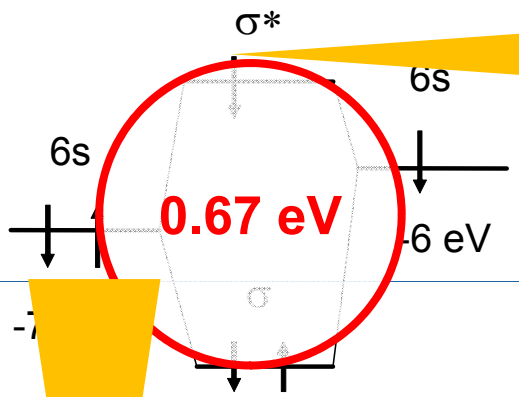
Trend prerserved from M-Au zu M-Au_n!

V. Pershina et al.

M-Au Bonding (Dimer)

Group 12

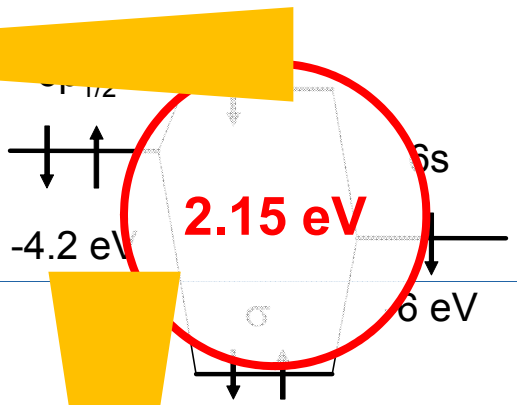
Hg-Au



Cn-Au

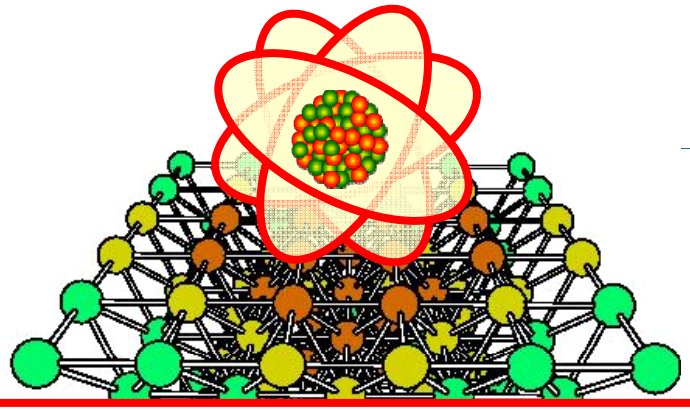
Group 14

Pb-Au



Fl-Au

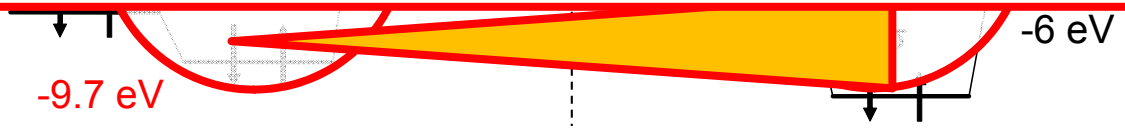
M on Au_n cluster



BUT: First experiment (PSI@FLNR Dubna):

Fl significantly less strongly bound on gold than Cn

R. Eichler et al., Radiochim. Acta 2010



Fl-Au bond: stronger than Cn-Au

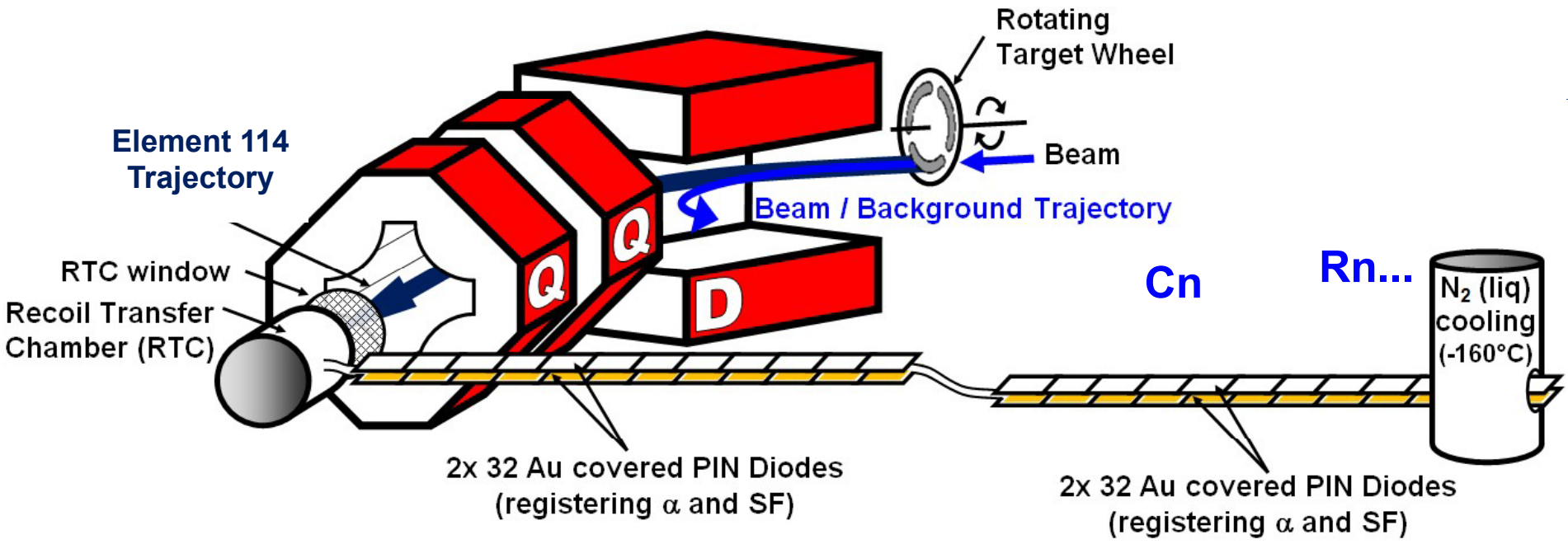
Trend preserved from M-Au zu M-Au_n!

V. Pershina et al.

TransActinide Separator and Chemistry Apparatus

TASCA

TASCA – COMPACT^2 configuration for flerovium (Z=114) chemistry



TASCA: A. Semchenkov et al., NIMB 266 (2008) 4153
TASCA Preseparator: Ch.E. Düllmann, Radiochim. Acta 99 (2011) 515
J. Even *et al.*, NIMA **638** (2011) 157

A. Yakushev et al.
Inorganic Chemistry **53 (2014) 1624**

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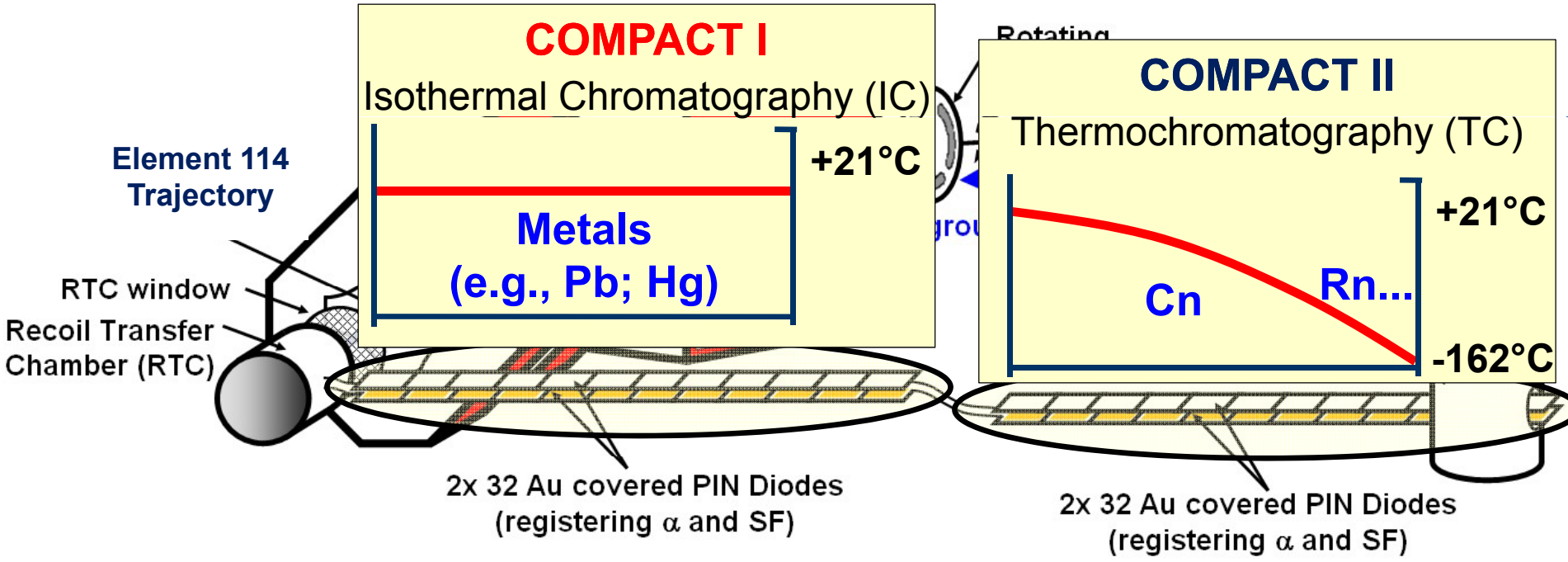

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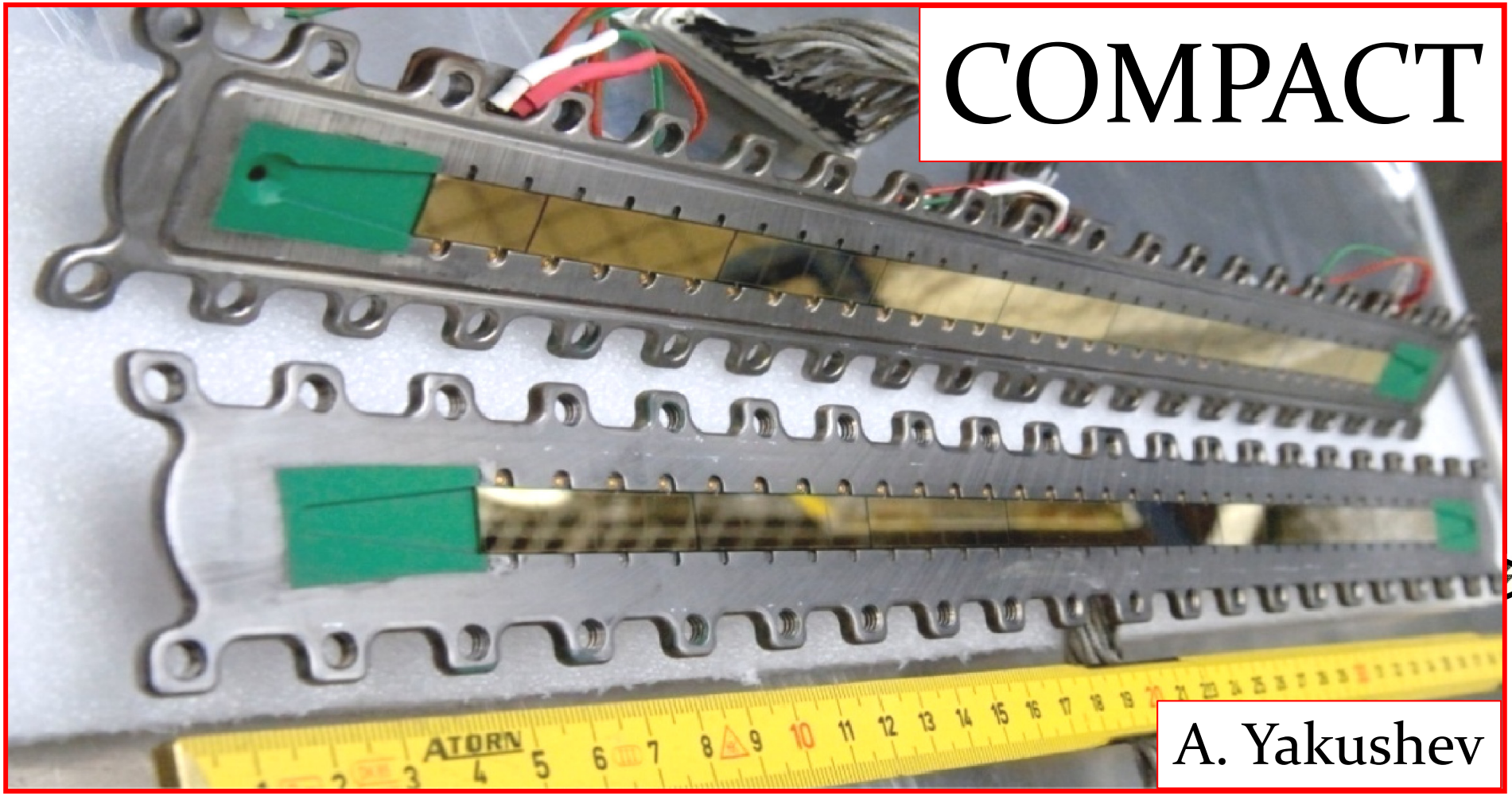

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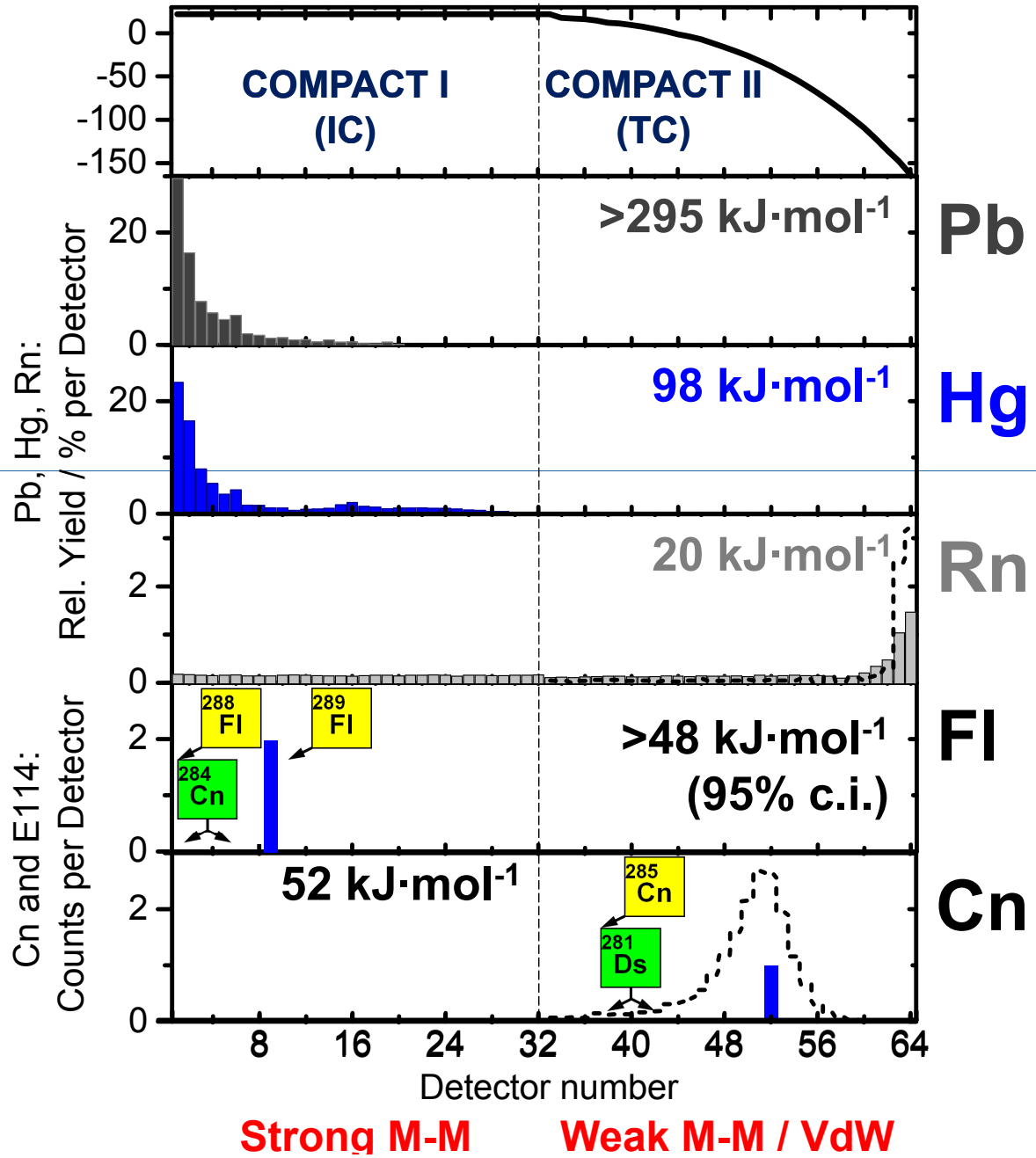
J. Even *et al.*, NIMA **638** (2011) 157

A. Yakushev et al.
Inorganic Chemistry **53 (2014) 1624**

News on Fl chemistry: directly comparing five elements



							18
		13	14	15	16	17	2 He
		5 B	6 C	7 N	8 O	9 F	10 Ne
		13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
11	12						
29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
	112 Cn		114 Fl				
111 Rg		113 ---		115 ---	116 Lv	117 ---	118 ---

65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Fl is a volatile metal, not noble-gas like

A. Yakushev et al.

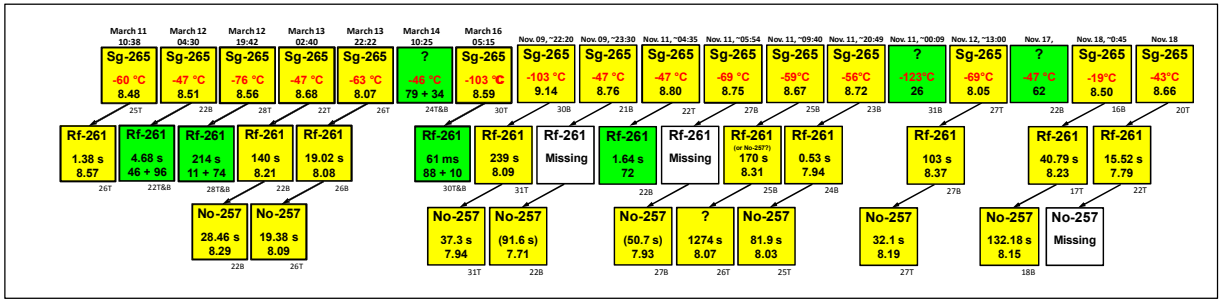
Inorganic Chemistry 53 (2014) 1624

2013 at RIKEN – after 40+ years SHE chemistry:

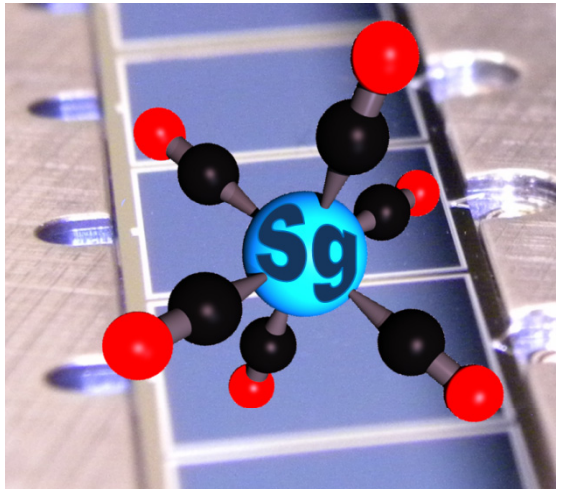
First step in the direction of organometallic SHE chemistry: $Sg(CO)_6$

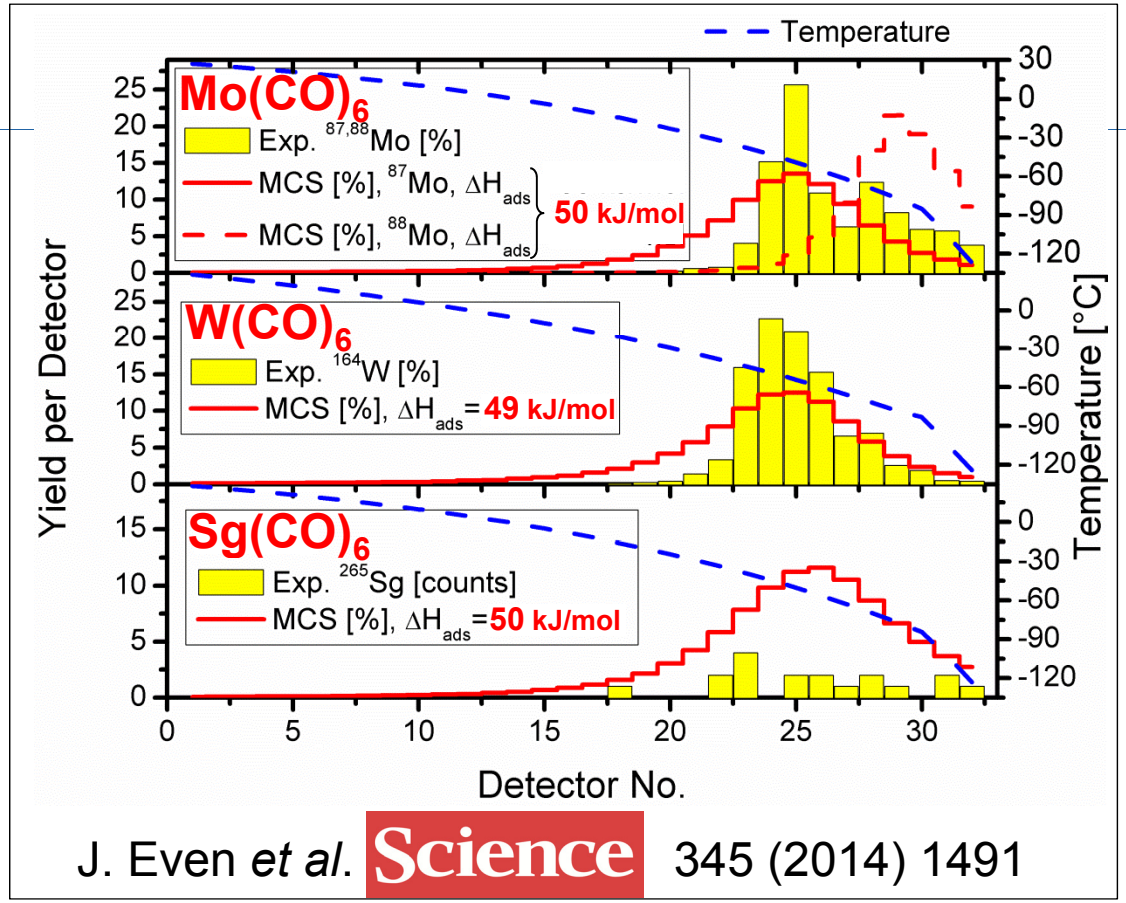
Group 6 $-\Delta H_{ads}$(theo) Pershina et al., JCP 2013

24 Cr	
42 Mo	48.1 kJ/mol
74 W	46.5 kJ/mol
106 Sg	46.2 kJ/mol



Hexacarbonyls:
$Mo(CO)_6$ / $W(CO)_6$ / $Sg(CO)_6$





J. Even *et al.* **Science** 345 (2014) 1491

see www.superheavies.de

A spectroscopy example

PRL 111, 112502 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Spectroscopy of Element 115 Decay Chains

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[7]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
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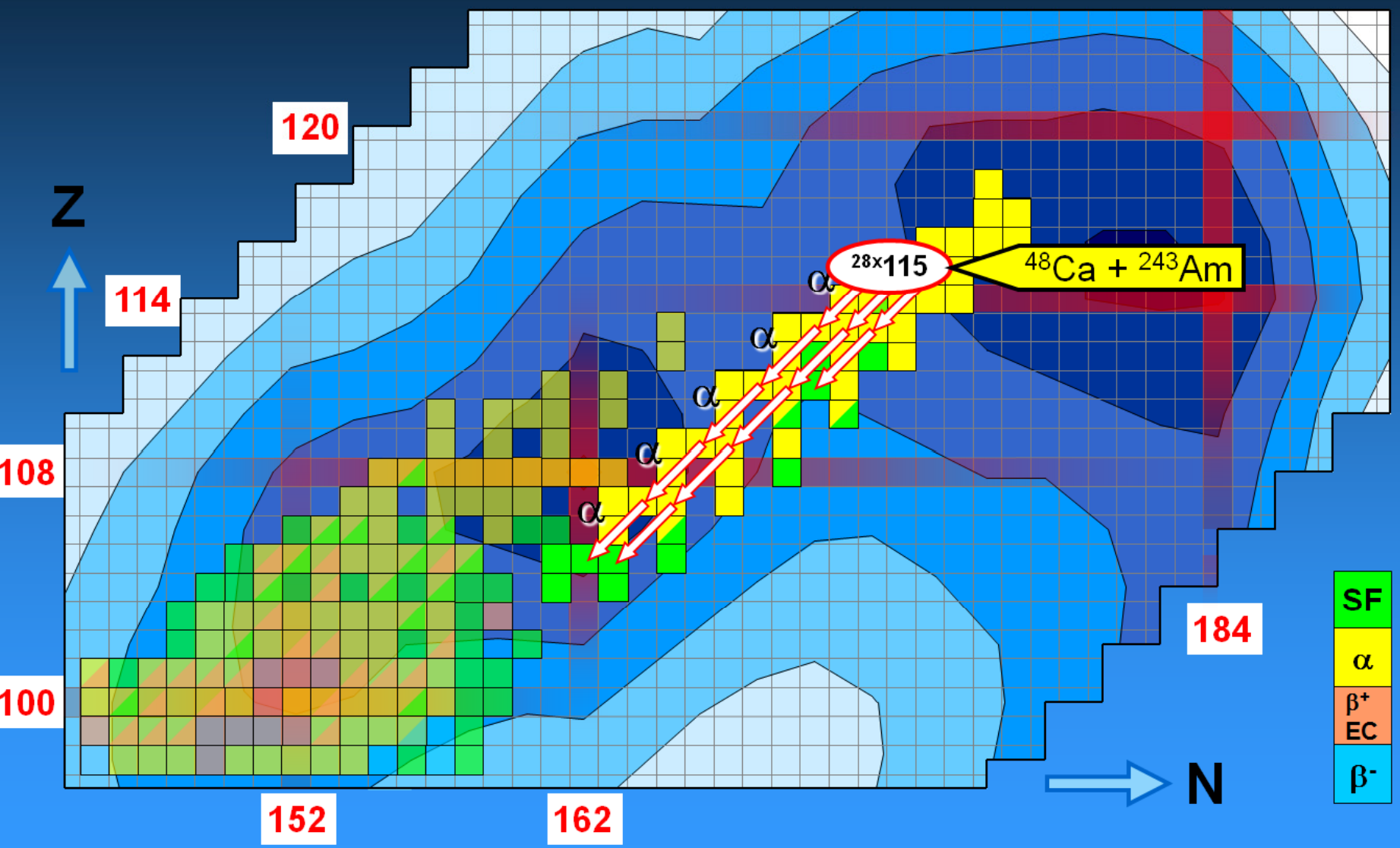
(Received 11 June 2013)

Special thanks to …

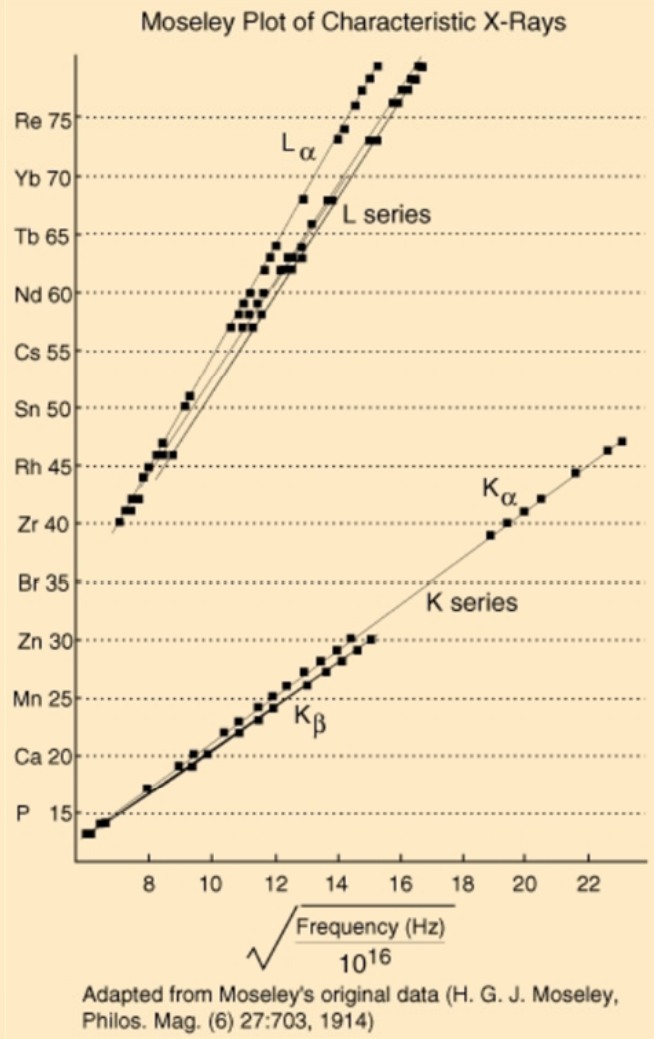
UNILAC ENSAR

Fingerprinting the SHE

- Direct measurement of Z

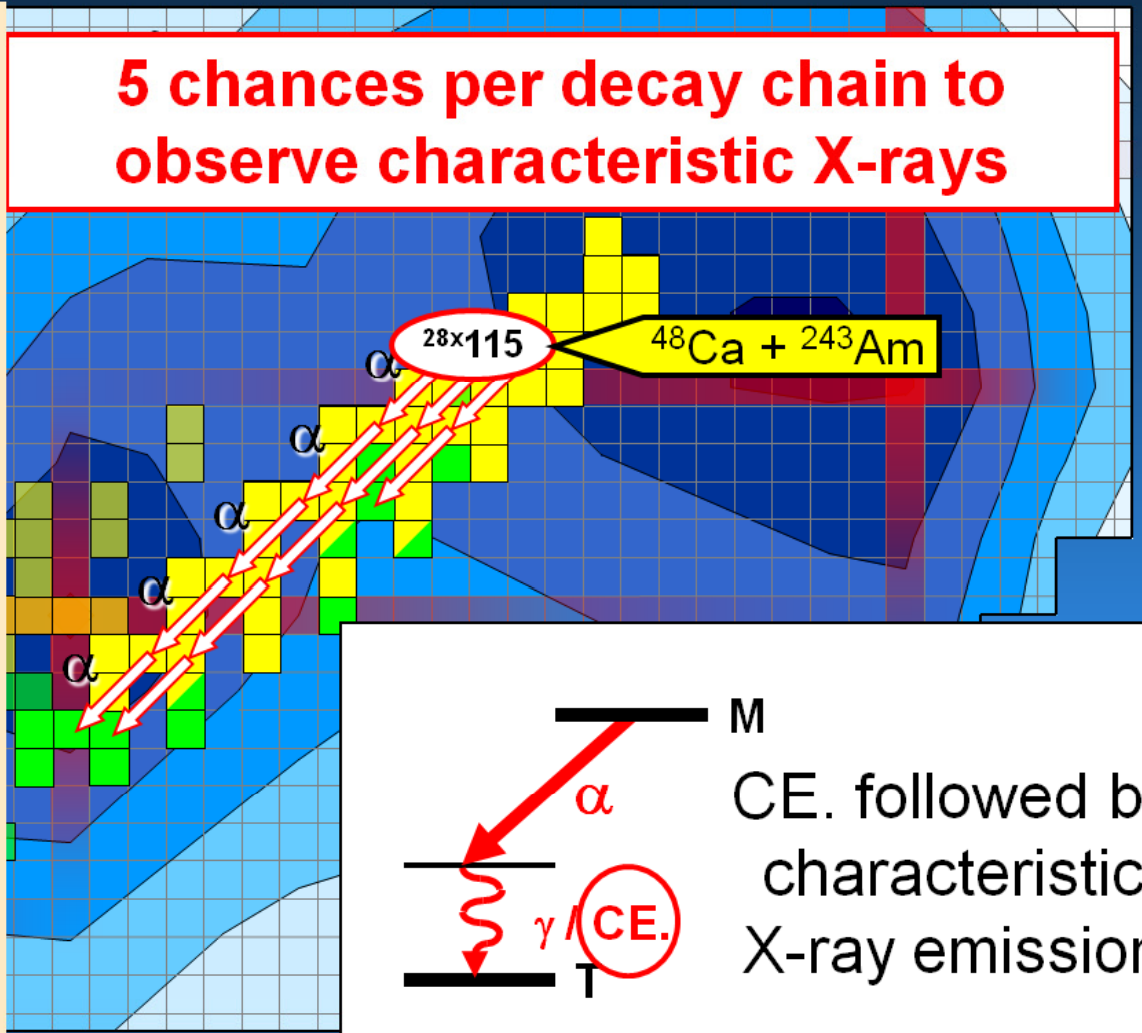


Fingerprinting the SHE
- Direct measurement of Z



$E_{X\text{-}ray}$ predicted to 0.1 keV for SHE

5 chances per decay chain to observe characteristic X-rays



CE. followed by characteristic X-ray emission

162

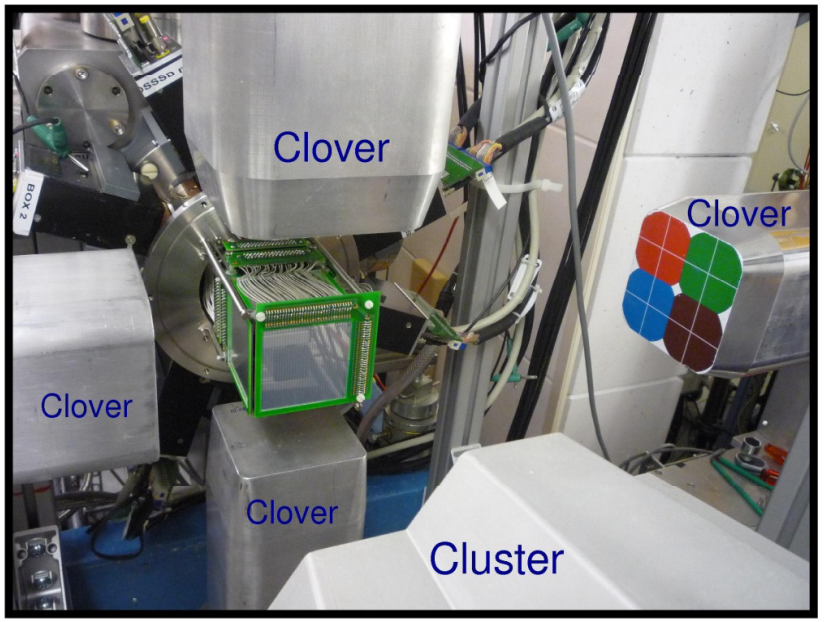
TASISpec

A highly efficient multi-coincidence spectroscopy setup for TASCA's very compact focal plane image

1 Implantation DSSSD (1024 pixels)
4 box–DSSSDs (1024 pixels)
=> ~80% α–detection efficiency

4 Ge Clover (4*4 crystals)
1 Ge Cluster (7 crystals)
=> ~40% γ–detection eff. at 150 keV

L–L Andersson et al., NIM A 622, 164 (2010)



Spokesperson: D. Rudolph (Lund U)

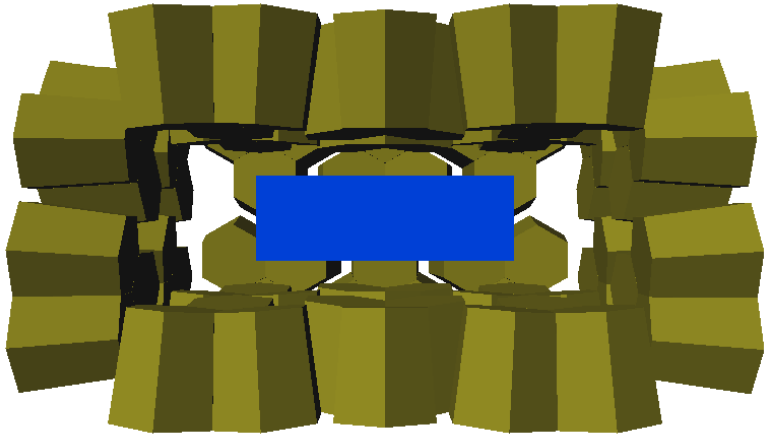
3 weeks, 1 $\mu A_{particle}$ ^{48}Ca on **0.83(1) mg/cm^2 ^{243}Am targets** on Ti backing

E_1: 242.1 MeV; 2.13(12)·10^{18} /E_2: 245.0 MeV, 3.89(23)·10^{18}; **Tot: 6·10^{18}**

TASCA Efficiency into TASISpec: 30(3)%

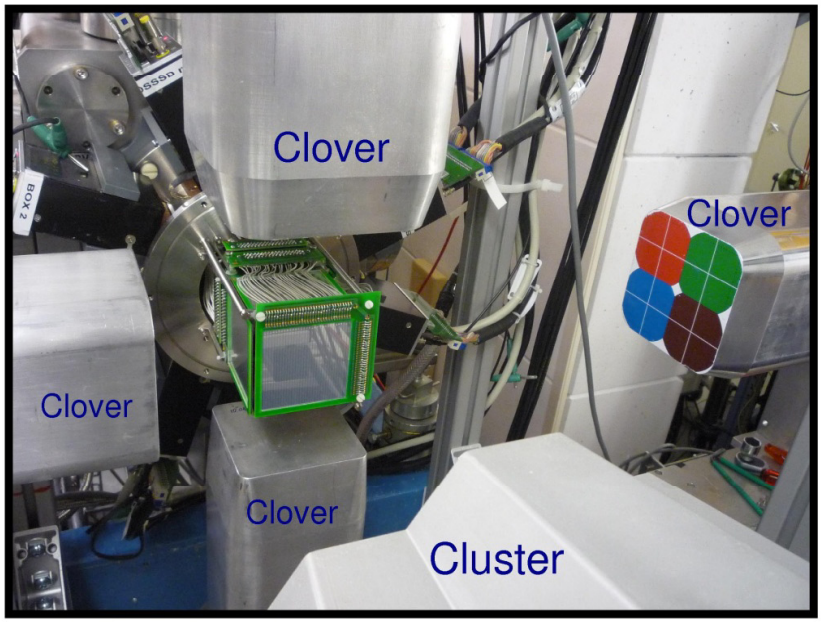
Trigger rate: 100-120 per second (particles in implantation DSSSD)

DEcay GAmma Spectrometer (DEGAS)



Next-generation HPGe cluster array
+ electronics for DESPEC in LEB

Courtesy J. Gerl



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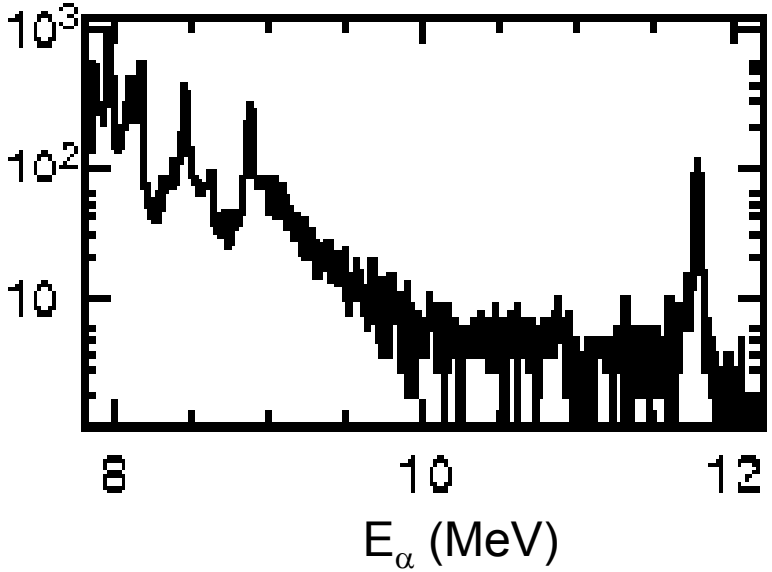
TASCA Efficiency into TASISpec: 30(3)%

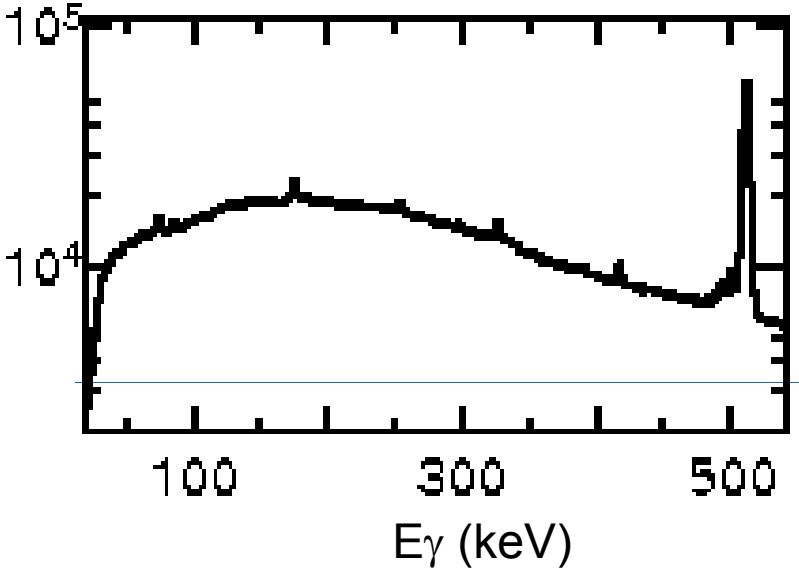
Trigger rate: 100-120 per second (particles in implantation DSSSD)

Clean alpha- and coincident gamma-spectra

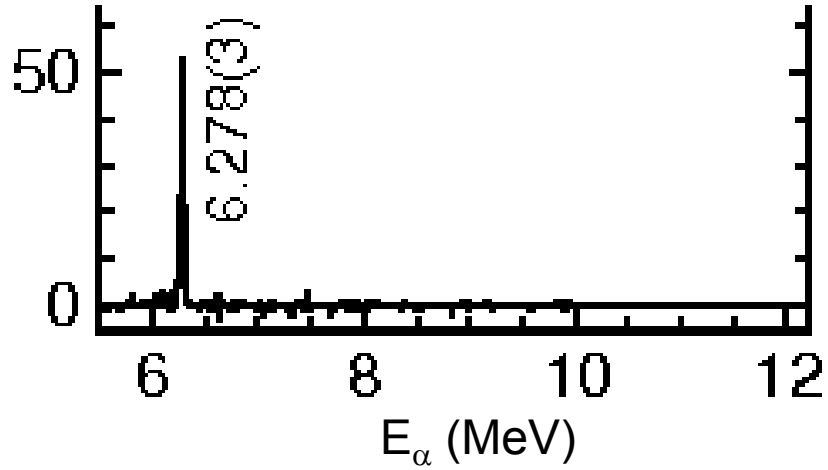
Total beam-off α-spectrum ($1.1 \cdot 10^6$ s)

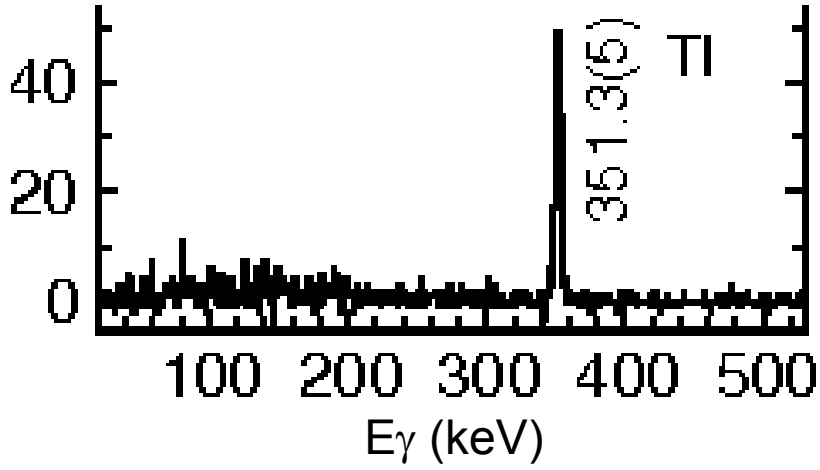


Coincident γ-spectrum ($8 \cdot 10^6$ entries)

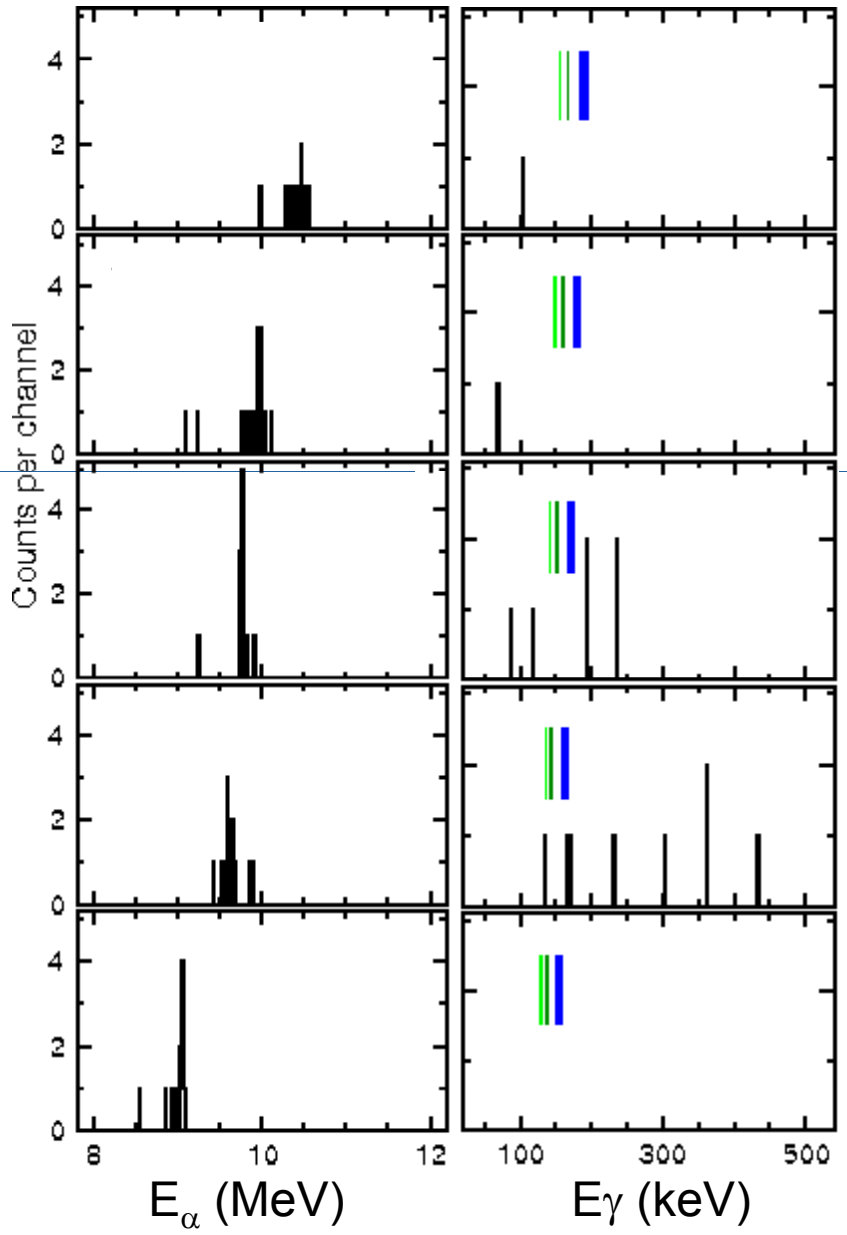


Looking at $^{211}Bi \rightarrow {}^{207}Tl$





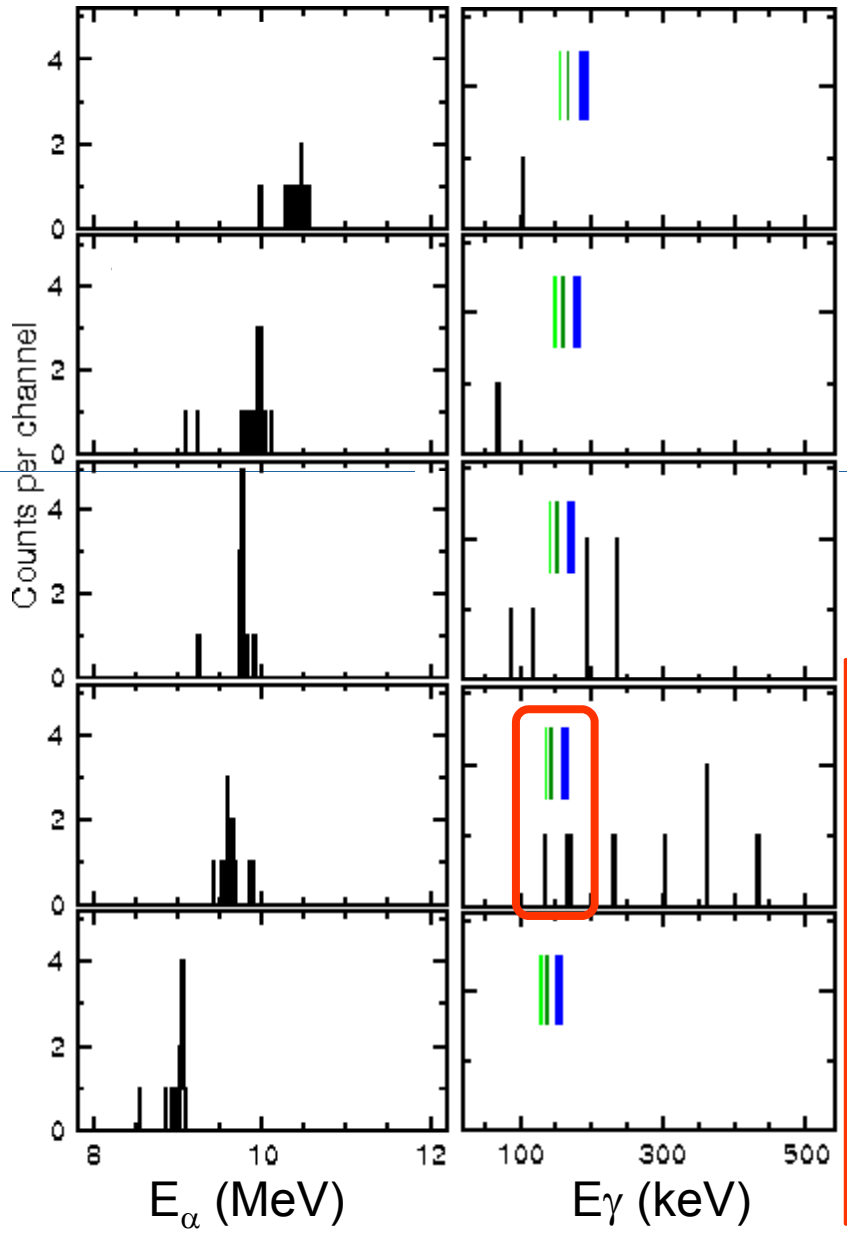
Spectra of the 22 "3n decay chains"



115 → 113	1x 105
113 → Rg	1x 69
Rg → Mt	1x 88; 1x 119; 2x 194 2x 237
Mt → Bh	1x 136; 1x 167; 1x 172; 1x 232; 1x 303; 2x 362; 1x 434
Bh → Db	Empty

Coincidence window: ~400 ns
Gamma energies are ±1 keV

Spectra of the 22 "3n decay chains"



115 → 113 1x 105

113 → Rg 1x 69

Rg → Mt 1x 88; 1x 119; 2x 194
2x 237

Mt → Bh 1x 136; 1x 167; 1x 172;
1x 232; 1x 303; 2x 362;
1x 434

Bh X-rays

$K_{\alpha 2}$: 136 keV
$K_{\beta 2}$: 167 keV
} accurate to better than 0.5%

T.A. Carlson et al., NPA 135 (1969) 57

Difference between neighboring Z: 3-4 keV

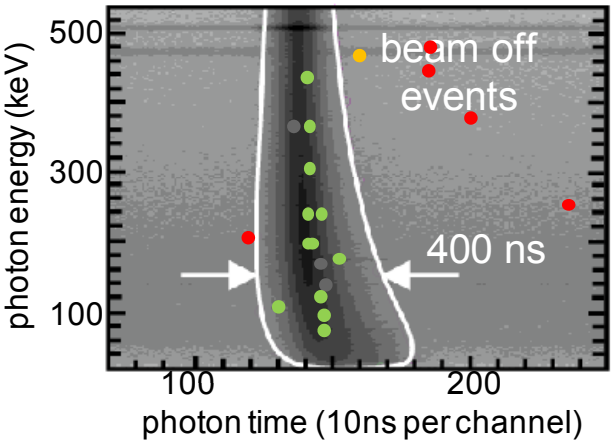
Gamma energies are 11 keV

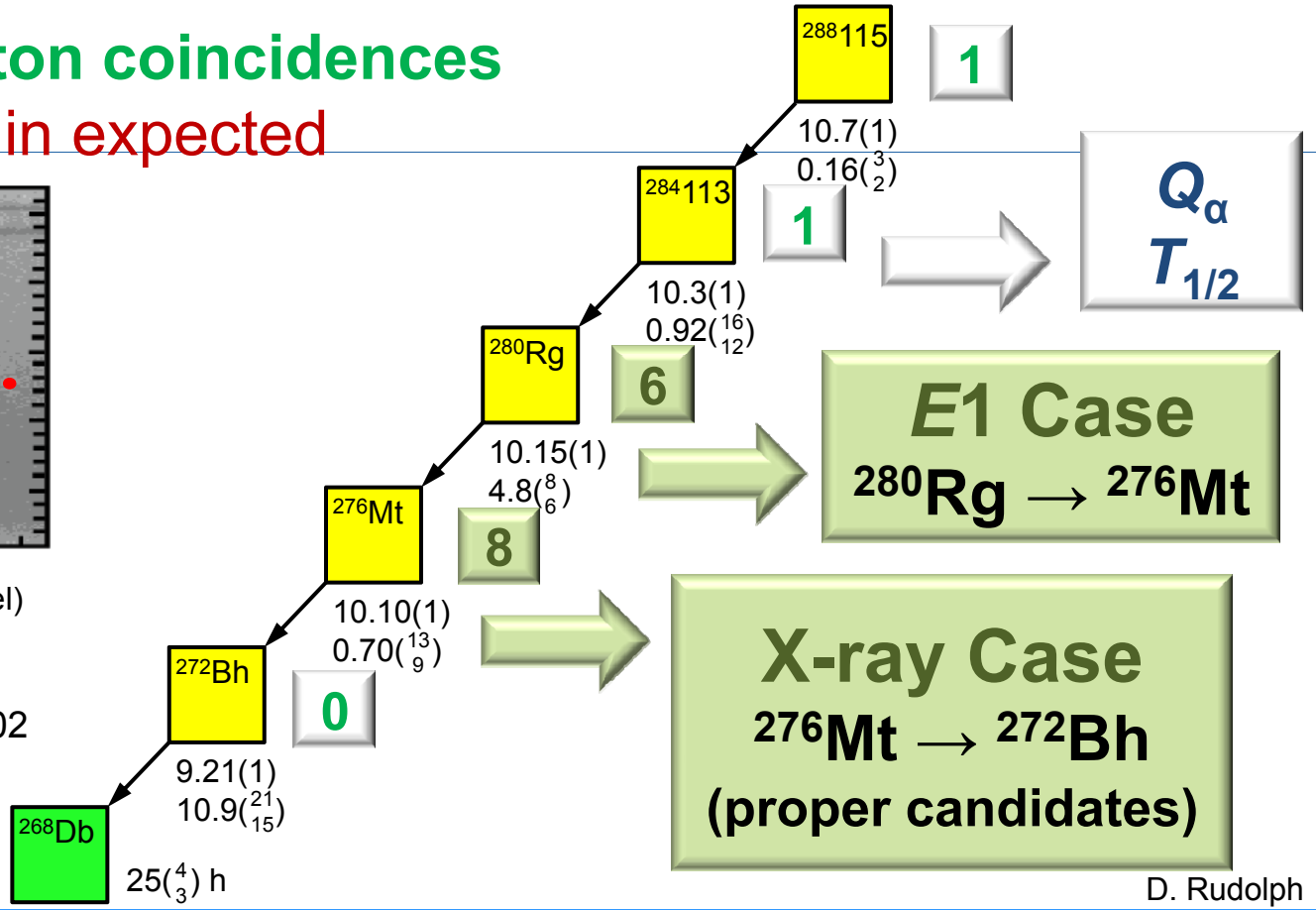
Results: $^{288}115$ (3n channel)

22 chains (out of 30) from TASISpec compatible with the
31 chains (out of 37) from DGFRS associated with $^{288}115$ (3n)

⇒ 53 "reference" chains called '3n' against which others are checked

16 prompt α-photon coincidences
2-3 of random origin expected



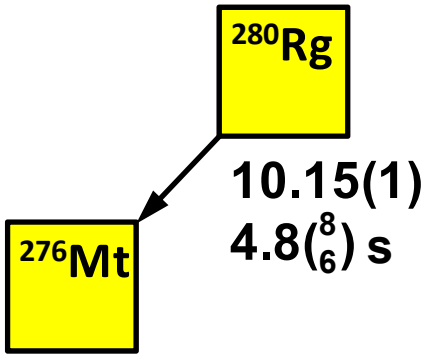


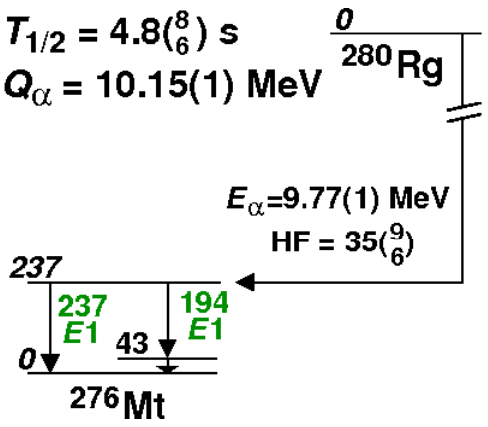
D. Rudolph *et al.*,
Phys. Rev. Lett. 111 (2013) 112502
Acta Phys. Pol. B 45 (2014) 263

U. Forsberg *et al.*,
EPJ Web Conf. 66 (2014) 02036

D. Rudolph

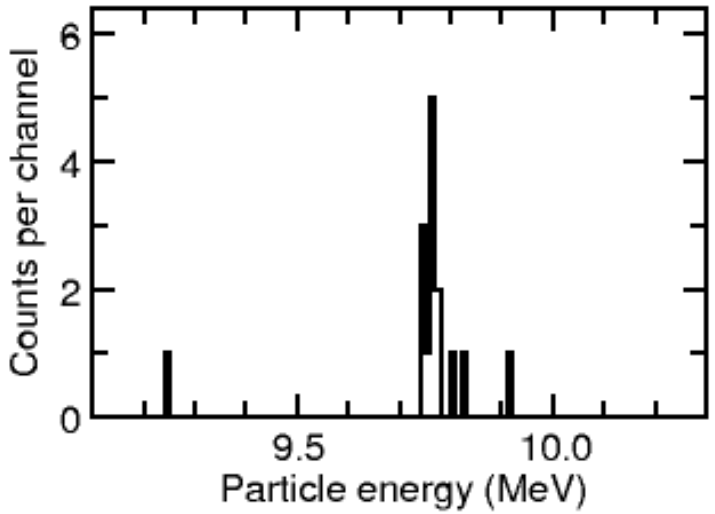
Results: $^{288}115$ (3n channel)



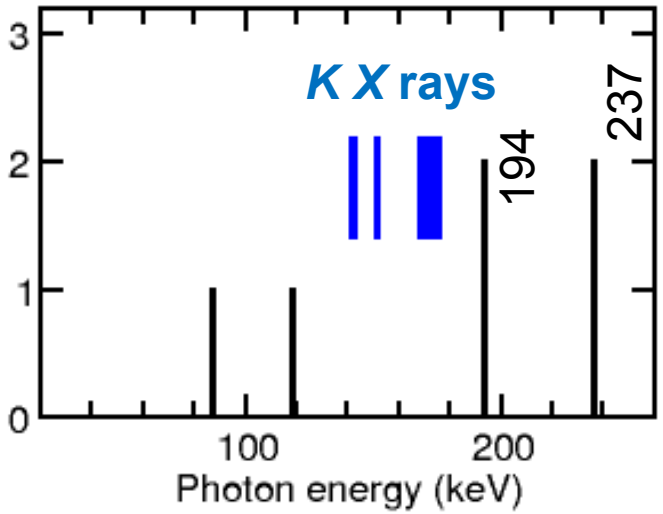


$^{280}Rg \rightarrow {}^{276}Mt$

α spectrum



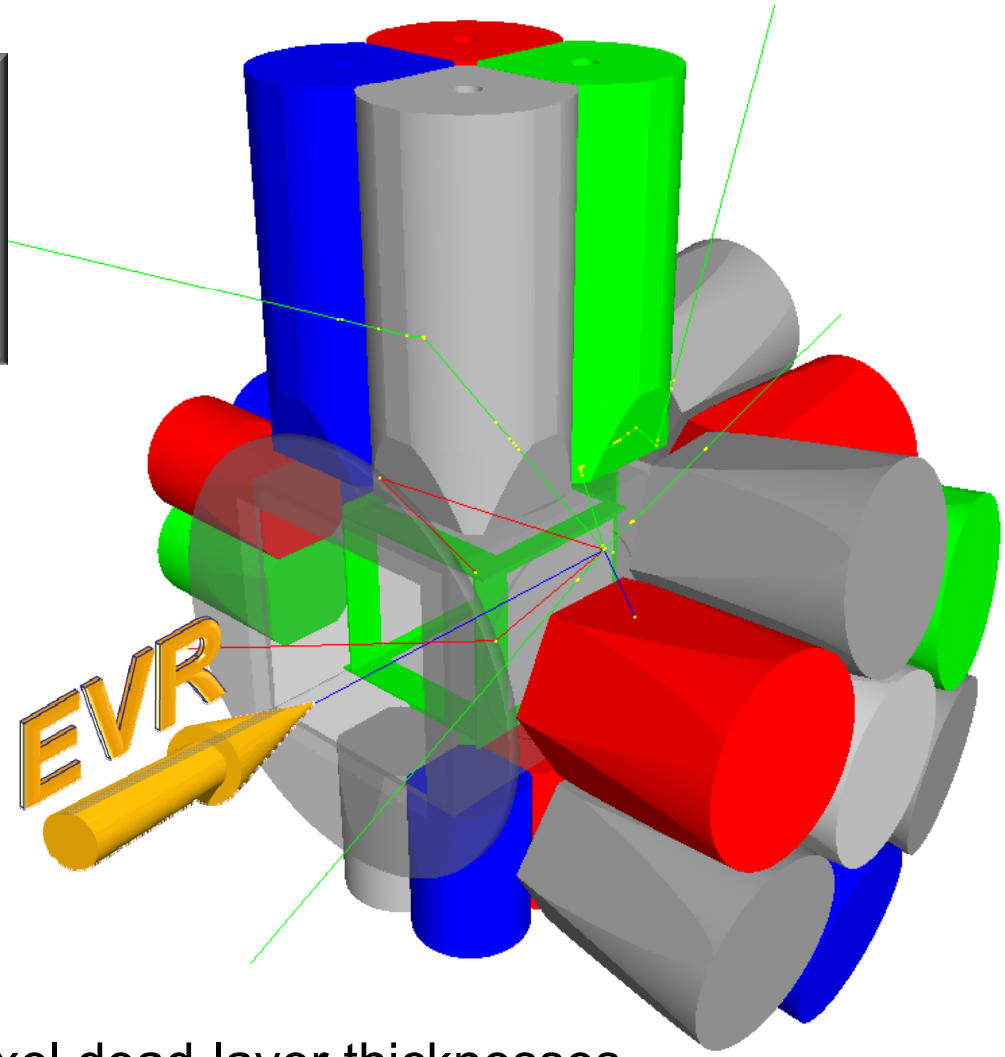
6x α-photon coinc.



D. Rudolph

TASISpec in virtual GEANT4 space

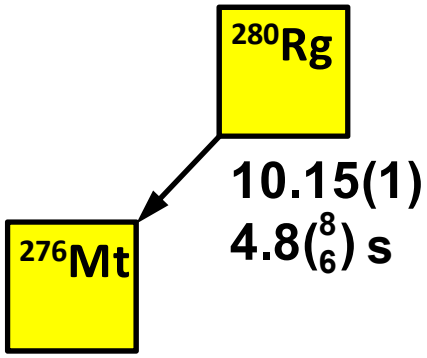
Self-consistent cross check of the experimental findings!

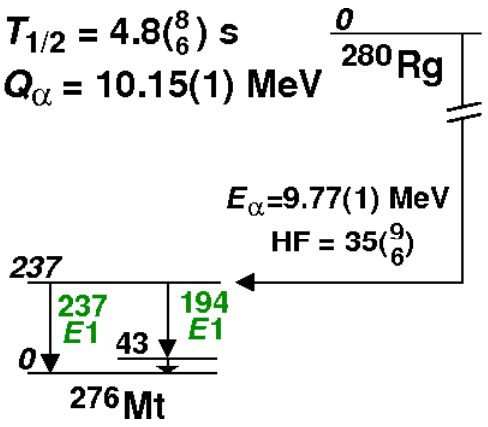


“Input level”: down to pixel-by-pixel dead-layer thicknesses …
“Output level”: takes care of summing of α, CE, and Auger energies …

L.G. Sarmiento et al., NIM A 667, 26 (2011)

Results: $^{288}115$ (3n channel)

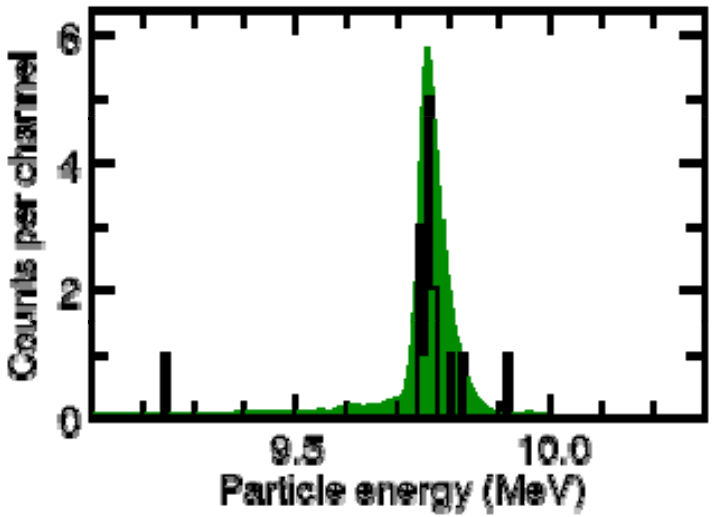




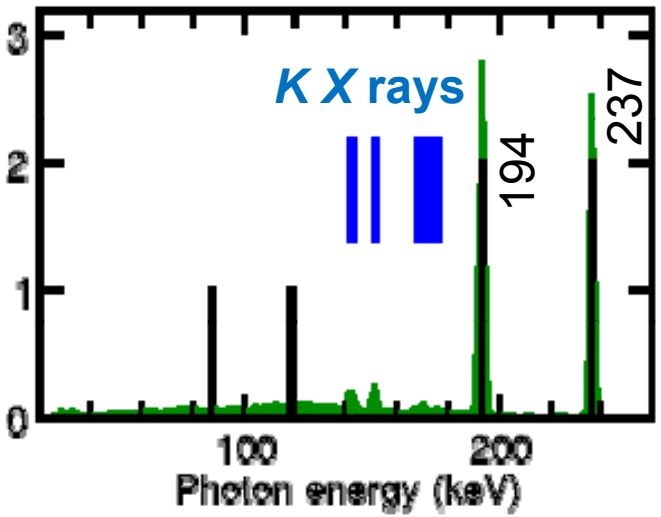
$E1$ Case

$^{280}Rg \rightarrow {}^{276}Mt$

α spectrum



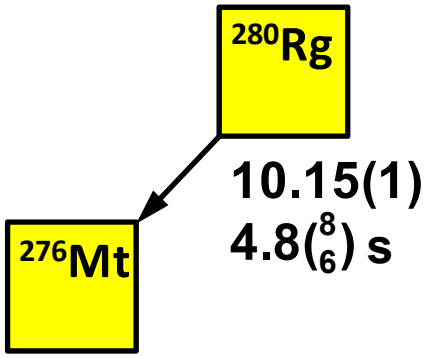
6x α-photon coinc.

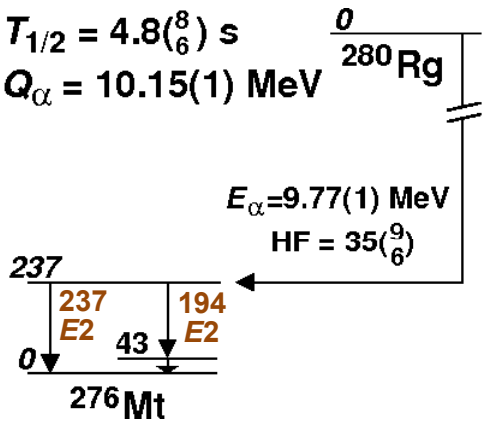


GEANT4 simulations: 100000 decays, normalized to number of α's

D. Rudolph

Results: $^{288}115$ (3n channel)

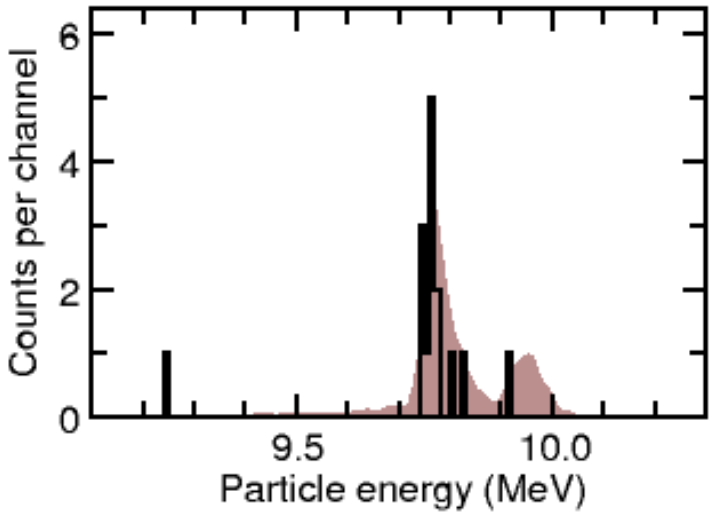




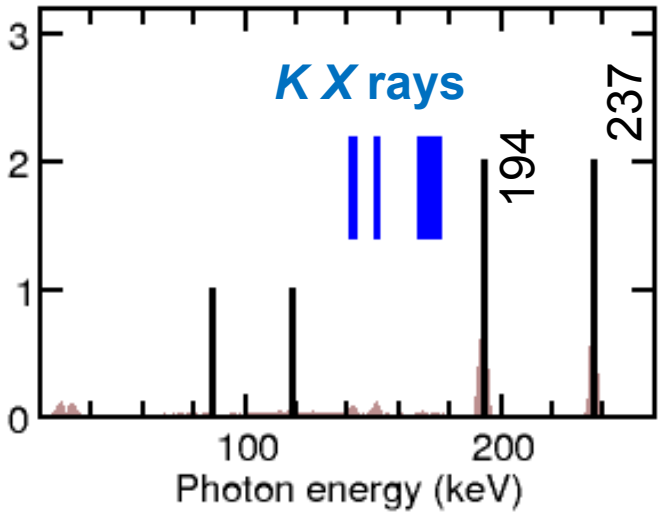
E2 Case

$^{280}Rg \rightarrow {}^{276}Mt$

α spectrum



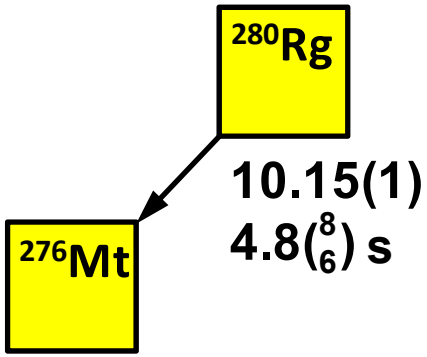
6x α-photon coinc.

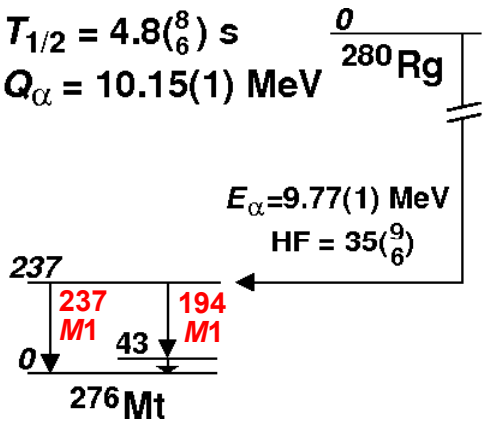


GEANT4 simulations: 100000 decays, normalized to number of α's

D. Rudolph

Results: $^{288}115$ (3n channel)

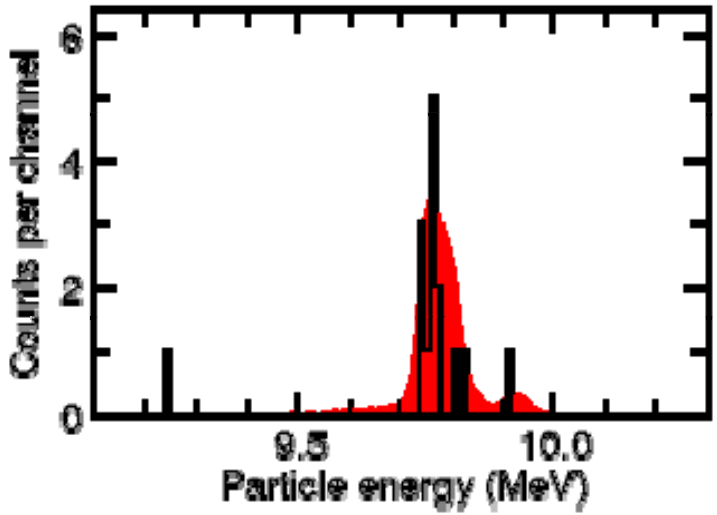


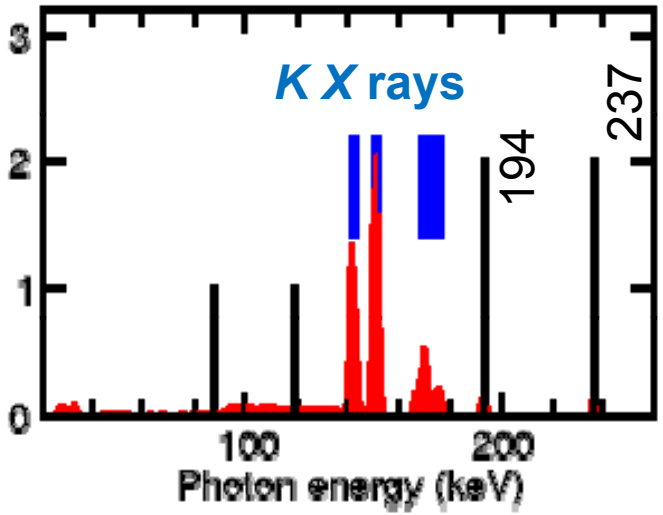


M1 Case

$^{280}Rg \rightarrow {}^{276}Mt$

M1 transitions would have provided THE perfect fingerprinting case!

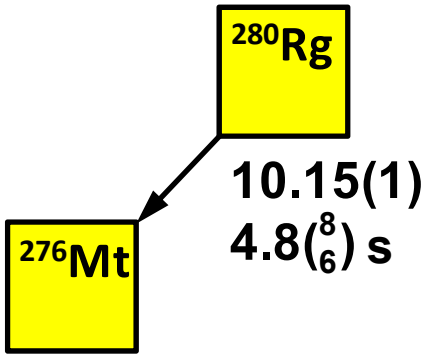


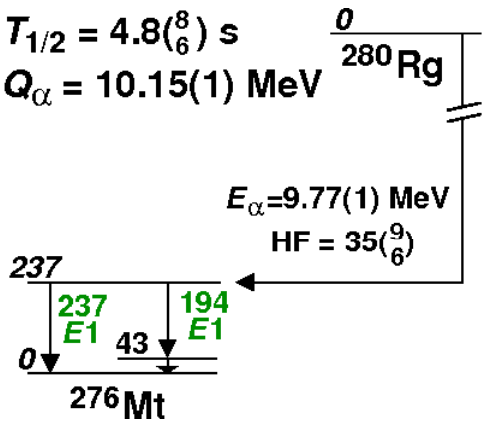


GEANT4 simulations: 100000 decays, normalized to number of α's

D. Rudolph

Results: $^{288}115$ (3n channel)



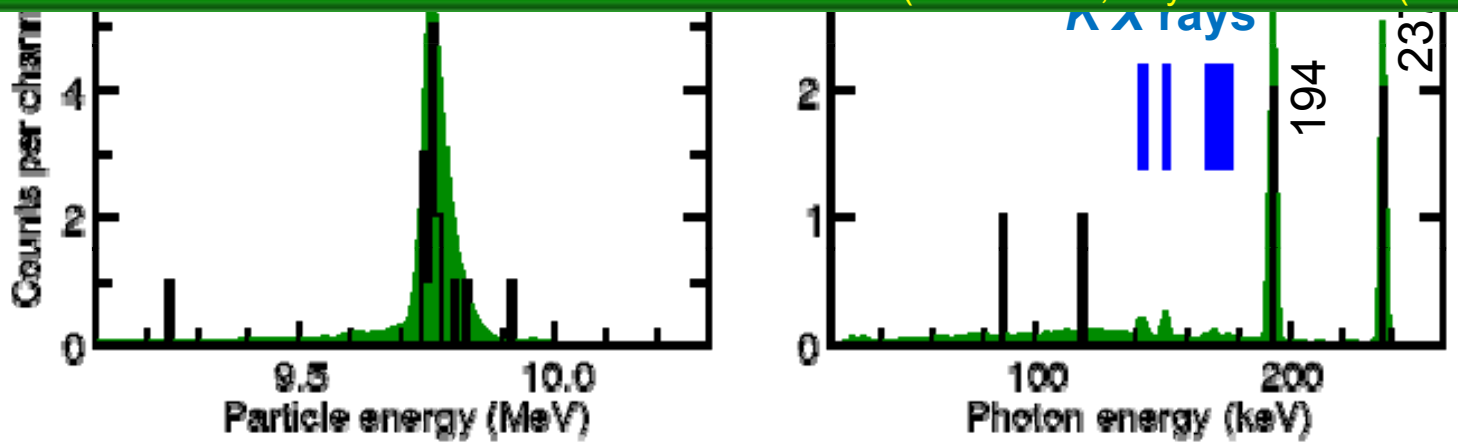


$E1$ Case

$^{280}Rg \rightarrow {}^{276}Mt$

$E1$ transitions put exciting contraints on nuclear structure theory!
Search for similar transitions in odd-A neighbors suggested.

(Y. Shi et al., Phys. Rev. C 90 (2014) 014308)



GEANT4 simulations: 100000 decays, normalized to number of α's

D. Rudolph

Superheavy Elements (SHE): a new collaboration in NUSTAR @ FAIR

Proposal to integrate new "Superheavy Element" collaboration in NUSTAR @ FAIR submitted to Board of Representatives (Summer '14)

Focus: synthesis, nuclear structure, atomic physics, nuclear chemistry experiments with elements Z ≥ 104

Existing facilties: SHIP, TASCA, SHIPTRAP, Chemistry beamline
Developments for high-intensity cw-Linac ongoing (HIM, GSI, U Frankfurt)

Complementary to existing NUSTAR activities at Super-FRS

Interim Structure:

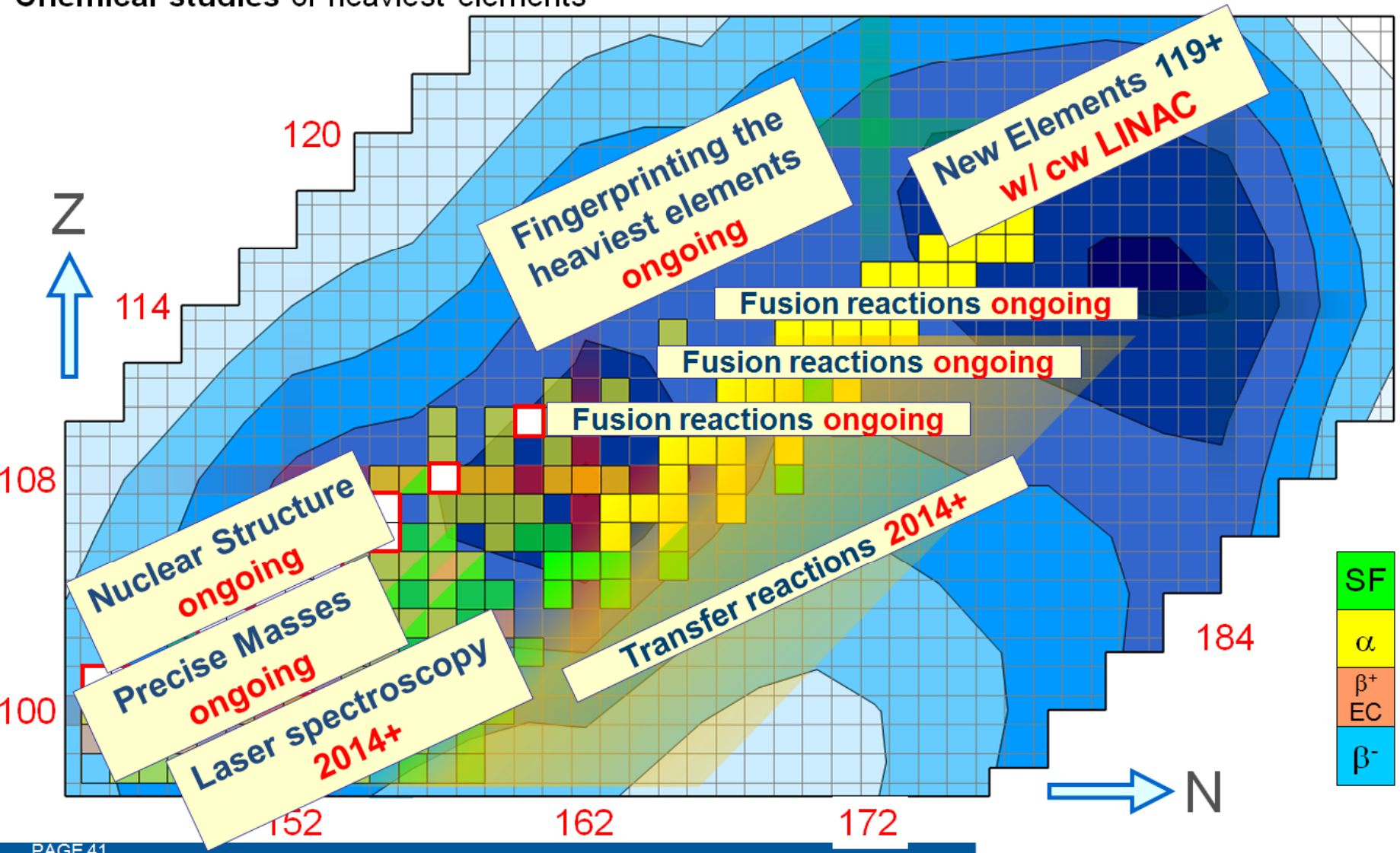
Spokesperson:	Ch.E. Düllmann (Univ. Mainz / GSI / HIM)
Deputy:	M. Block (GSI)
Technical manager:	A. Yakushev (GSI)

Currently includes 8 German and 17 international institutes

Endorsed by NUSTAR Collaboration Committee: Sept. 25, 2014

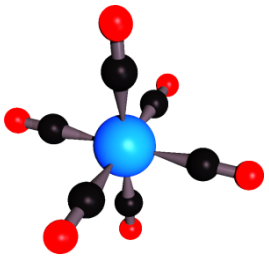
SHE research program "Days 0/1"

-**Synthesis** of new elements and isotopes in fusion + transfer reactions
-**Nuclear structure** studies by decay spectroscopy and high-precision mass measurements
-**Laser spectroscopy** beyond fermium
-**Chemical studies** of heaviest elements

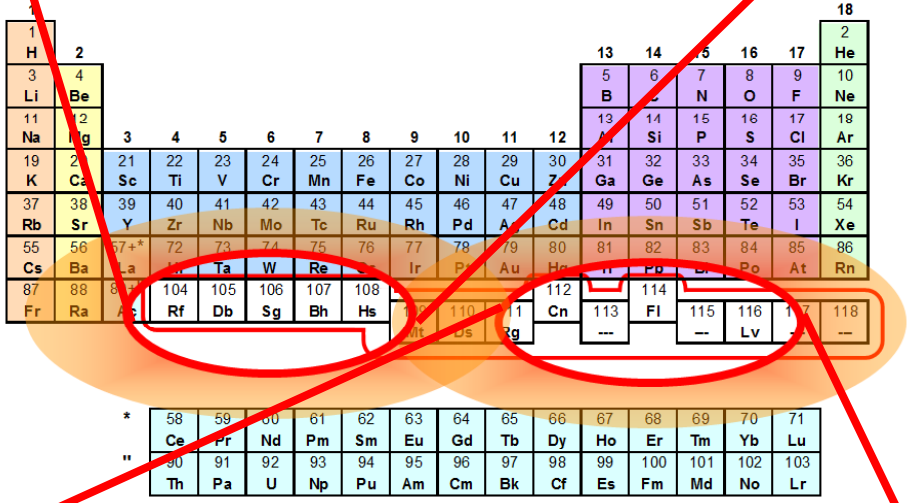


SHE research program "Days 0/1"

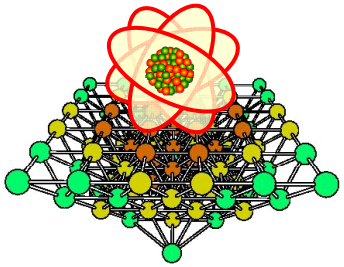
Z~106: New single molecule chemical SHE compounds



$Sg(CO)_6$, $Bh(CO)_x$



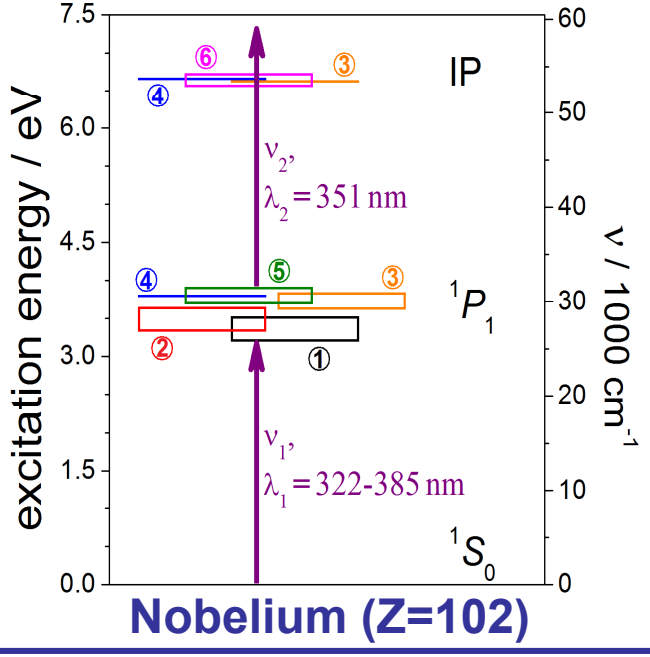
Z~114: Single atom gas chromatography



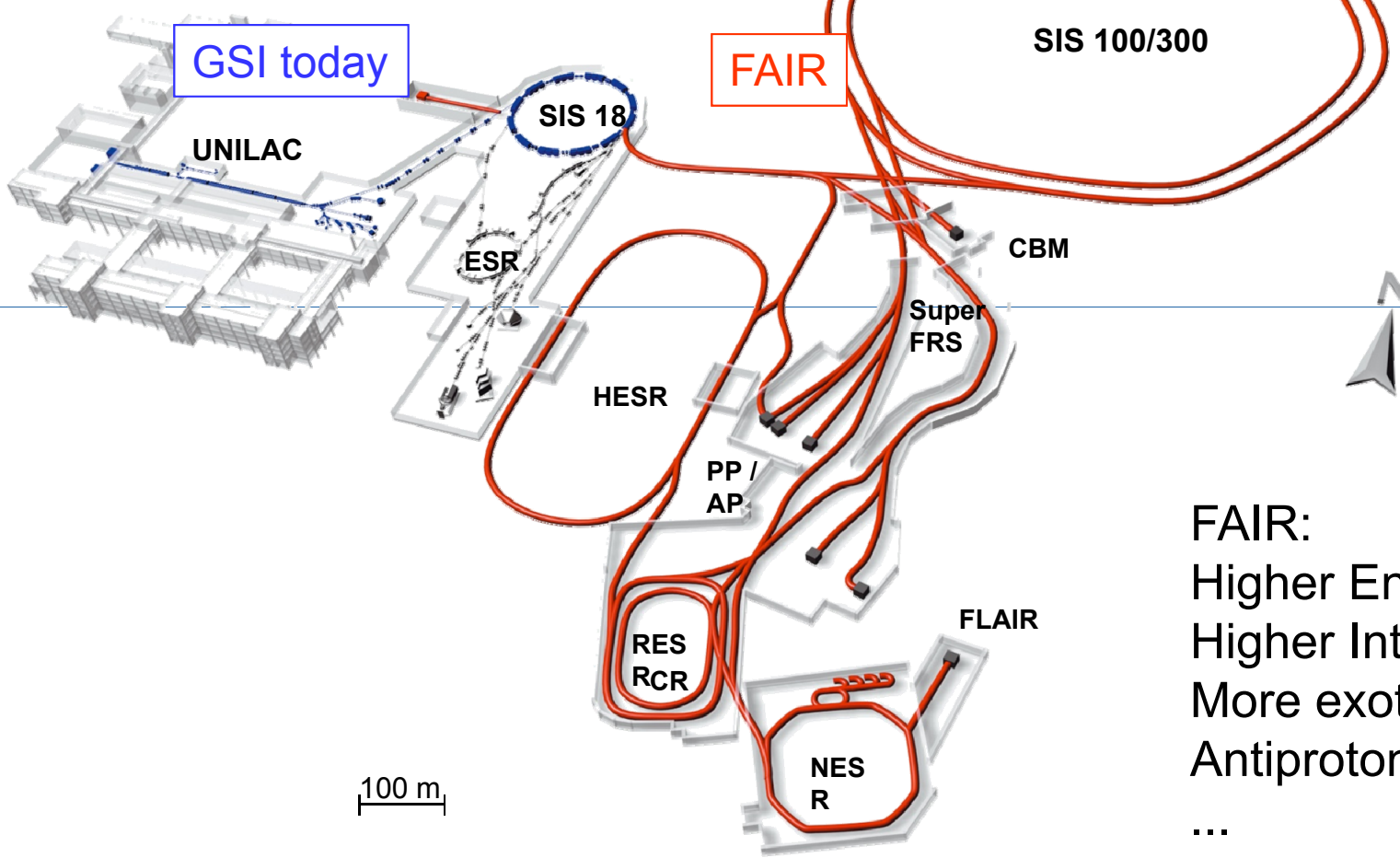
$113\text{-}Au_n$; $Fl\text{-}Au_n$

- Testing the architecture of the periodic table of the elements
- Understanding relativistic effects on electronic shell structure

Resonant laser ionization spectroscopy around No (Z=102) to search for atomic levels



Outlook



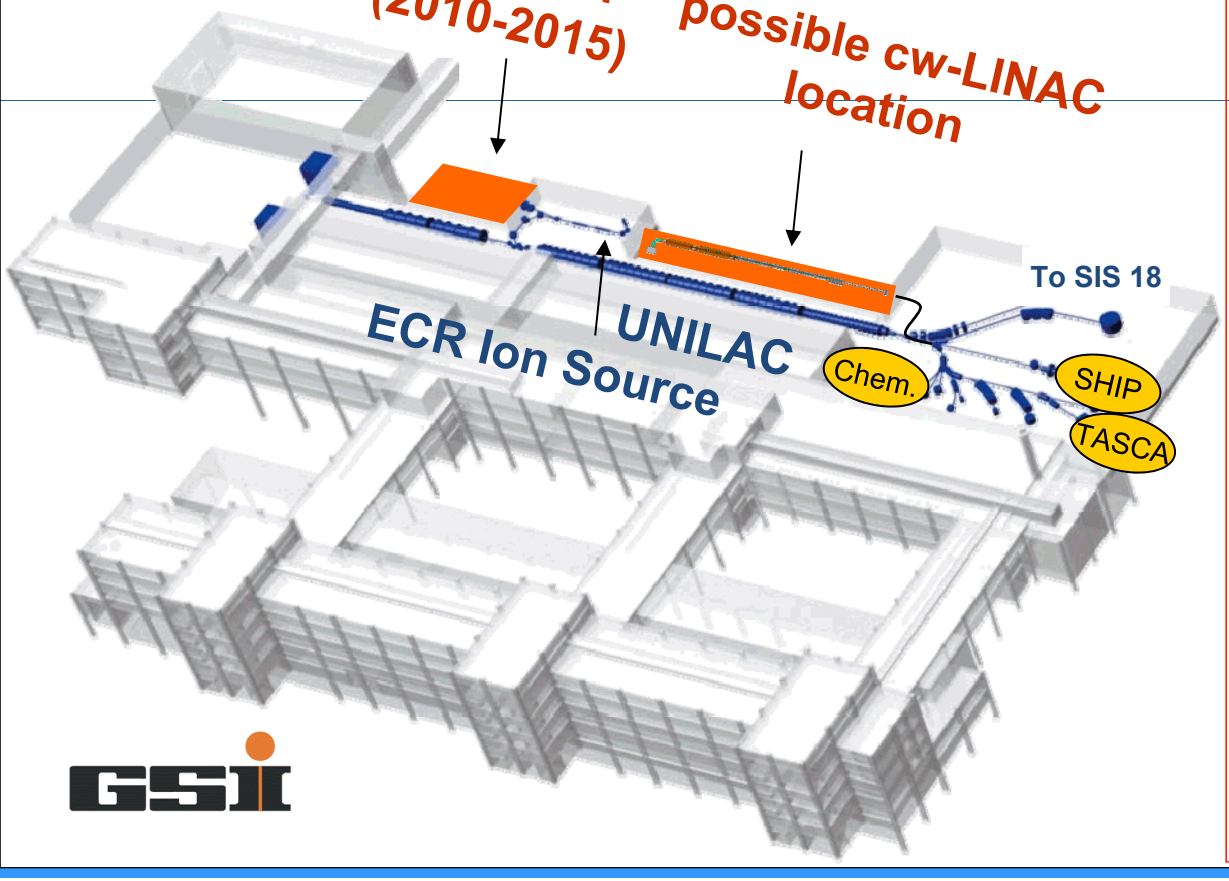
FAIR:
Higher Energy
Higher Intensity
More exotic species
Antiprotons
...

GSI Helmholtzzentrum für Schwerionenforschung mbH
Facility for Antiproton and Ion Research

Toward a Dedicated SHE LINAC

UNILAC not suited for simultaneous
- **FAIR** (A>180, ≤3 Hz, 100 μs pulses)
- **SHE operation** (A<80, long duty cycle)

HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz



Paving the way for dedicated superconducting cw-LINAC:

Energy: 3.5-7.5 MeV/u

Uncertainty: <3 keV/u

Duty cycle: 100%

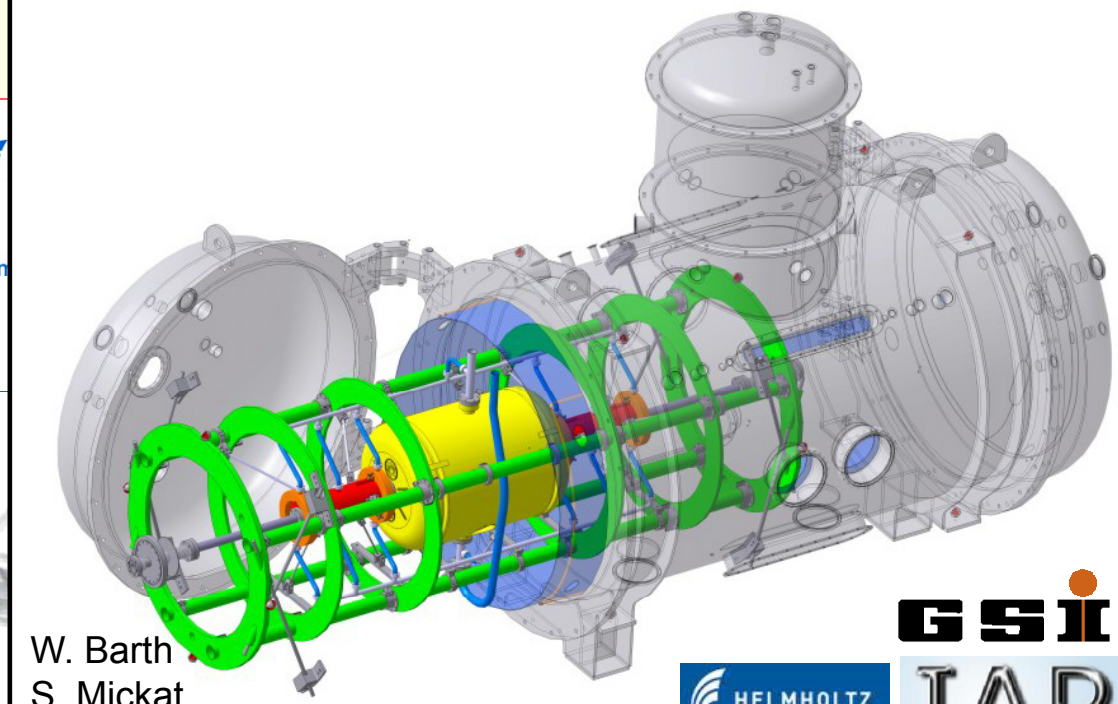
Staged Approach:

1) Construct first cavity as a prototype to demonstrate feasibility.
   Commissioning: 2015
2) Construct multicell string during POF 3 (2015-2019)
   Useful for SHE research, synergies for FAIR!
3) Contruct full linac

Toward a Dedicated SHE LINAC

(A>180, ≤3 Hz, 100 μs pulses)

peration (A<80, long duty cycle)



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U. Ratzinger

GSI

HELMHOLTZ Institut Mainz

IAP

Paving the way for dedicated superconducting cw-LINAC:

Energy: 3.5-7.5 MeV/u

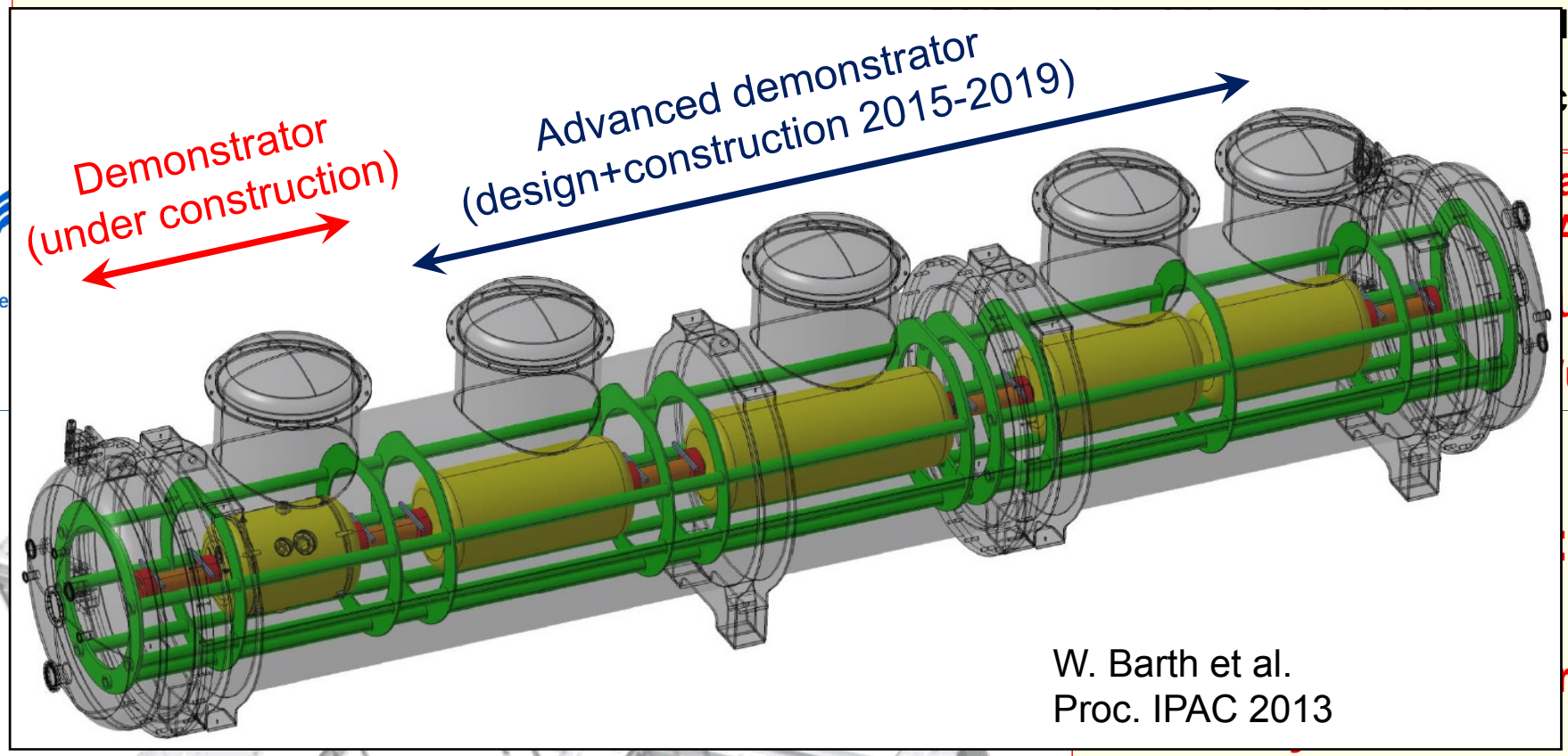
Uncertainty: <3 keV/u

Duty cycle: 100%

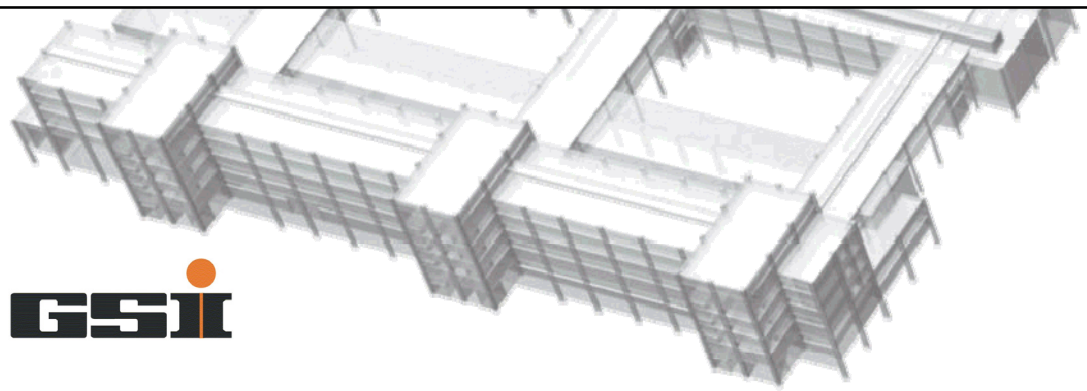
Staged Approach:

1) Construct first cavity as a prototype to demonstrate feasibility.
   Commissioning: 2015
2) Construct multicell string during POF 3 (2015-2019)
   Useful for SHE research, synergies for FAIR!
3) Contruct full linac

Toward a Dedicated SHE LINAC



W. Barth et al.
Proc. IPAC 2013



Commissioning: 2015

2) Construct multicell string during POF 3 (2015-2019) Useful for SHE research, synergies for FAIR!

3) Contruct full linac

Summary

- Superheavy element research was and is a pillar of the GSI research portfolio, shall be so for FAIR
  - **Synthesis** experiments:
    -sensitive searches for E119/120
    -confirmation of element 117 and new data on chains
  - Z-identification via X-rays possible / nuclear **spectroscopy**
    -experiment on element 115 decay chains yields two X-ray candidates
    -first nuclear structure details in region of SHE near island of stability
  - Precision **mass mesaurements** at SHIPTRAP / TRIGA-TRAP
    -direct mapping of shell effects in the region of the heaviest elements
  - **Laser spectroscopy** beyond fermium (Z>100)
    -first experiment starts next week
  - **Chemical studies** around Z=114 / on new Sg compounds
    -Fl is a volatile metal
    -with $Sg(CO)_6$ on the way to organometallic compounds
- Outlook: balancing FAIR construction and (SHE) research; need cw linac