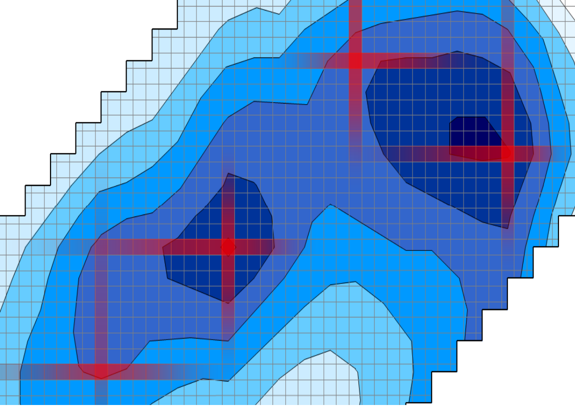
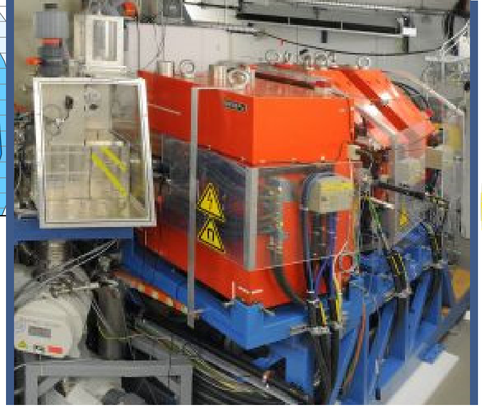
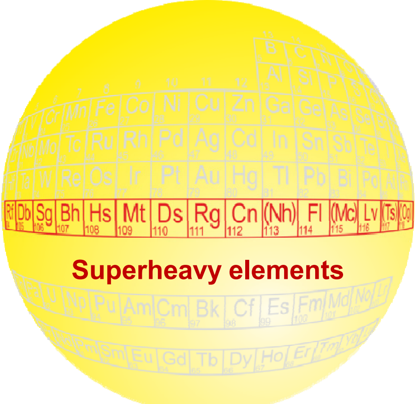
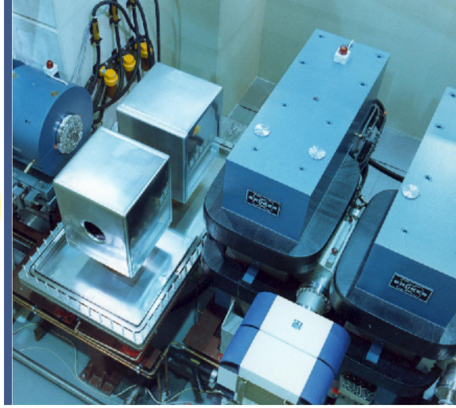






SHE Experiments at the UNILAC

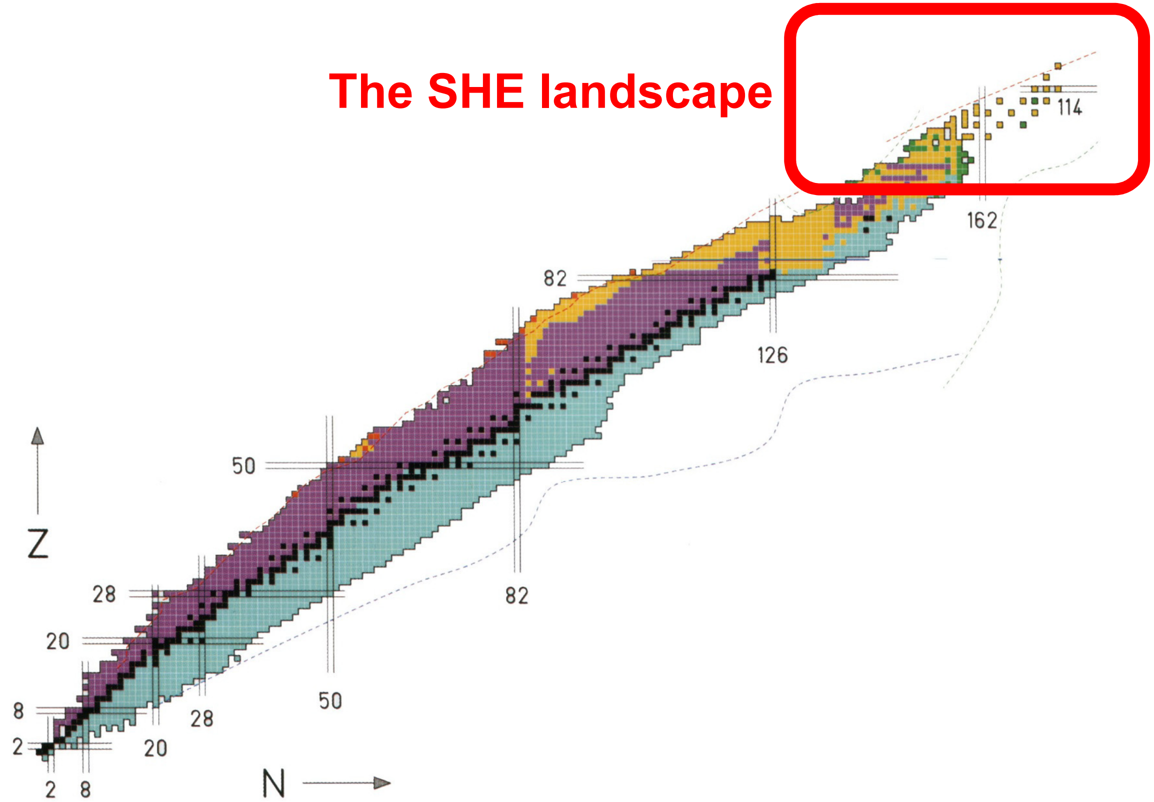
Christoph E. Düllmann / Michael Block

UNILAC Workshop
August 22, 2016

GSI
HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz

The Chart of Nuclei

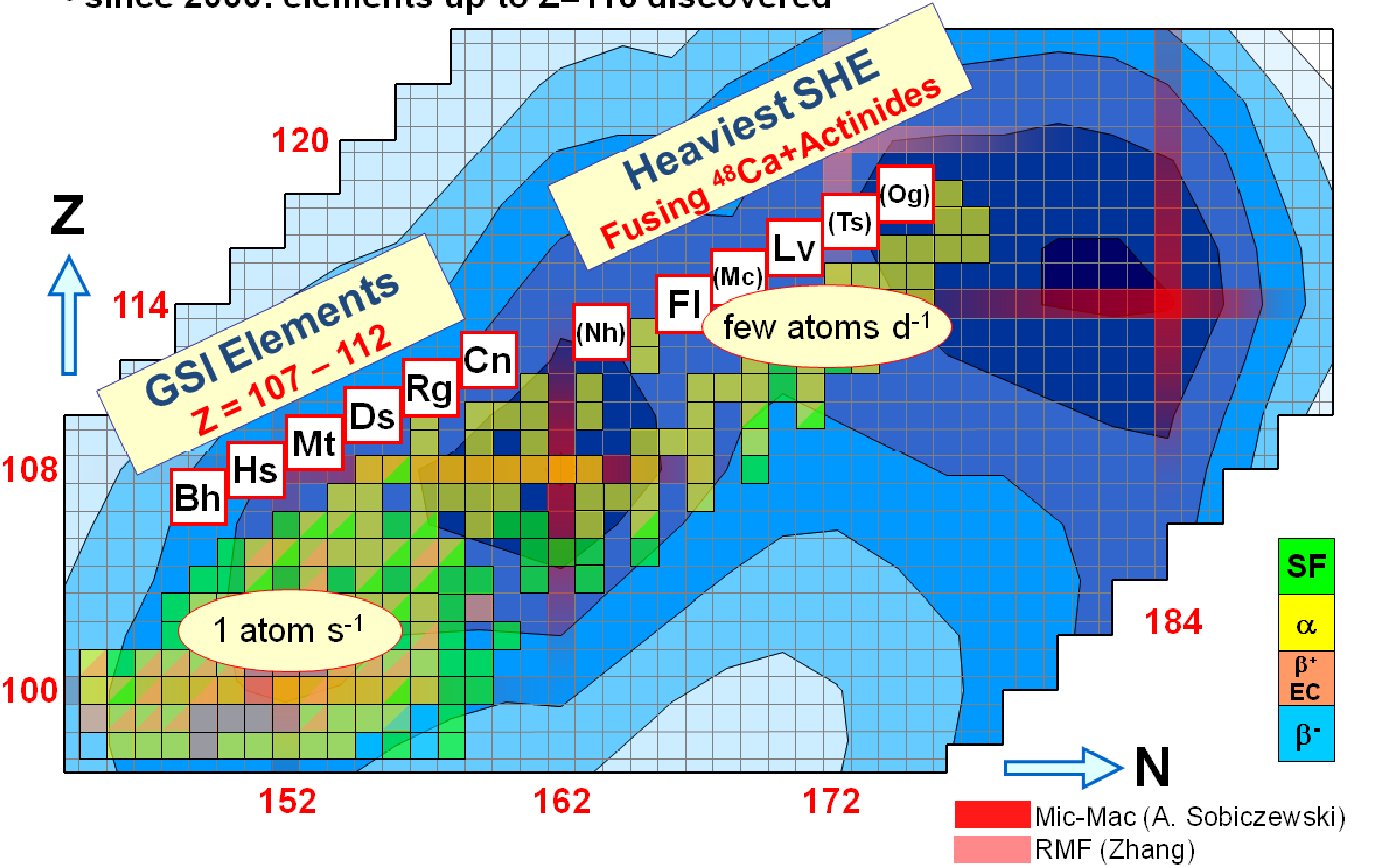
- SHN exist only due to shell effects created by the strong force
- studies of SHN test the strong interaction at extreme Z and N
- relevant for modeling of element creation in the Universe and predicting properties of neutron stars



- Are there still distinct magic numbers in SHN?
- What is the strength and extension of proton and neutron shell effects?
- What is the heaviest nucleus that can exist?
- Boundaries of *Island of Stability* and properties of nuclides within

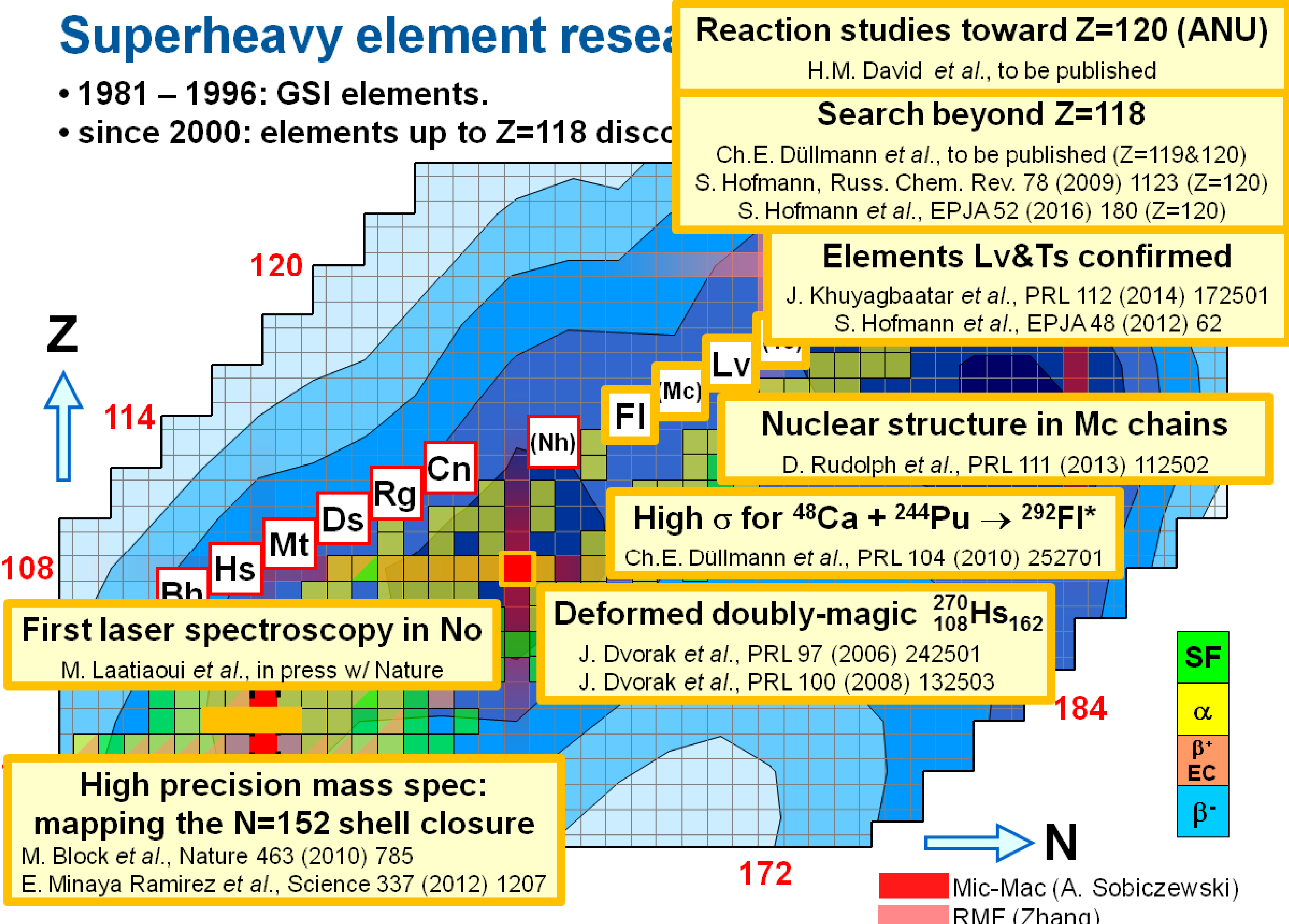
Superheavy element research – current status

- 1981 – 1996: GSI elements.
- since 2000: elements up to Z=118 discovered



Superheavy element resea

- 1981 – 1996: GSI elements.
- since 2000: elements up to Z=118 disco



Superheavy element chemistry – Current status

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+* 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+" 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)

*	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

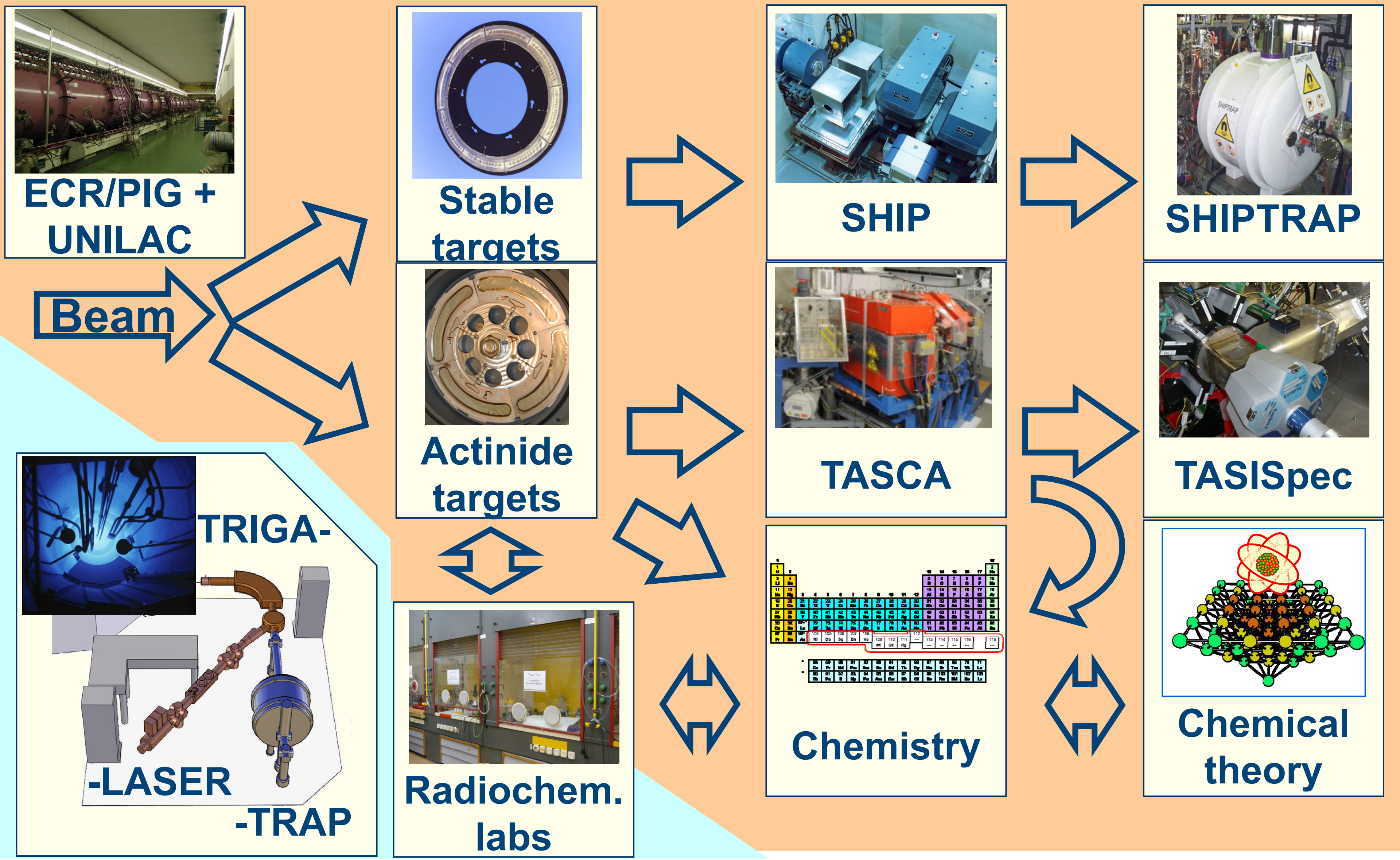
First chemical study of Sg (Z=106)
M. Schädel *et al.*, Nature 388 (1997) 55

Chemical study of Nh, Fl
A. Yakushev *et al.*, Inorg. Chem. 53 (2014) 1624
A. Yakushev *et al.*, in preparation

First chemical study of Hs (Z=108)
Ch.E. Düllmann *et al.*, Nature 418 (2002) 859

First "new" SHE compound: $Sg(CO)_6$
J. Even *et al.*, Science 345 (2014) 1491

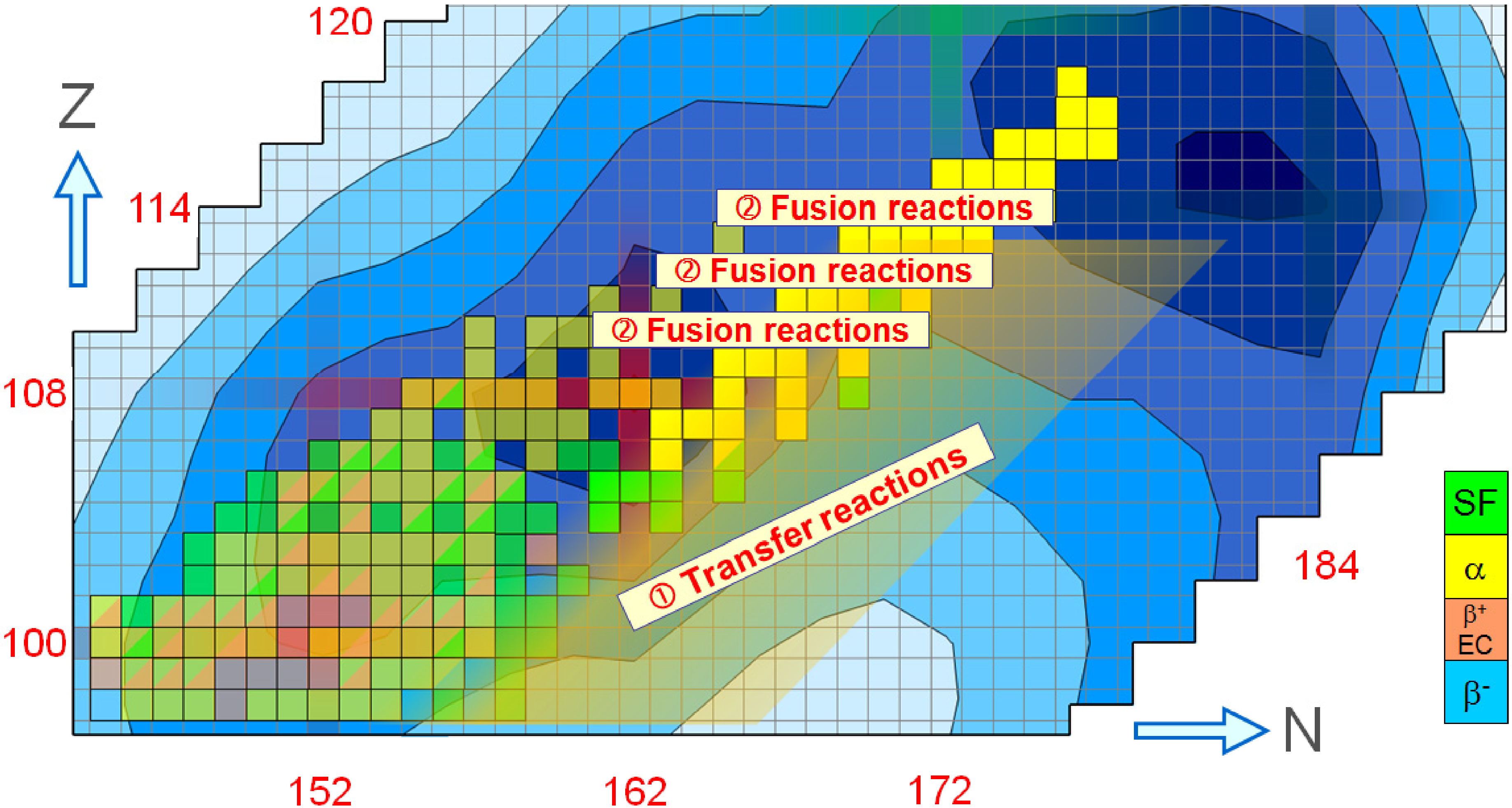
GSI/HIM/U Mainz: A unique combination for SHE research



Superheavy element physics program in POF 3

Reduced GSI research program, parallel to FAIR detector tests using the "free" UNILAC beam

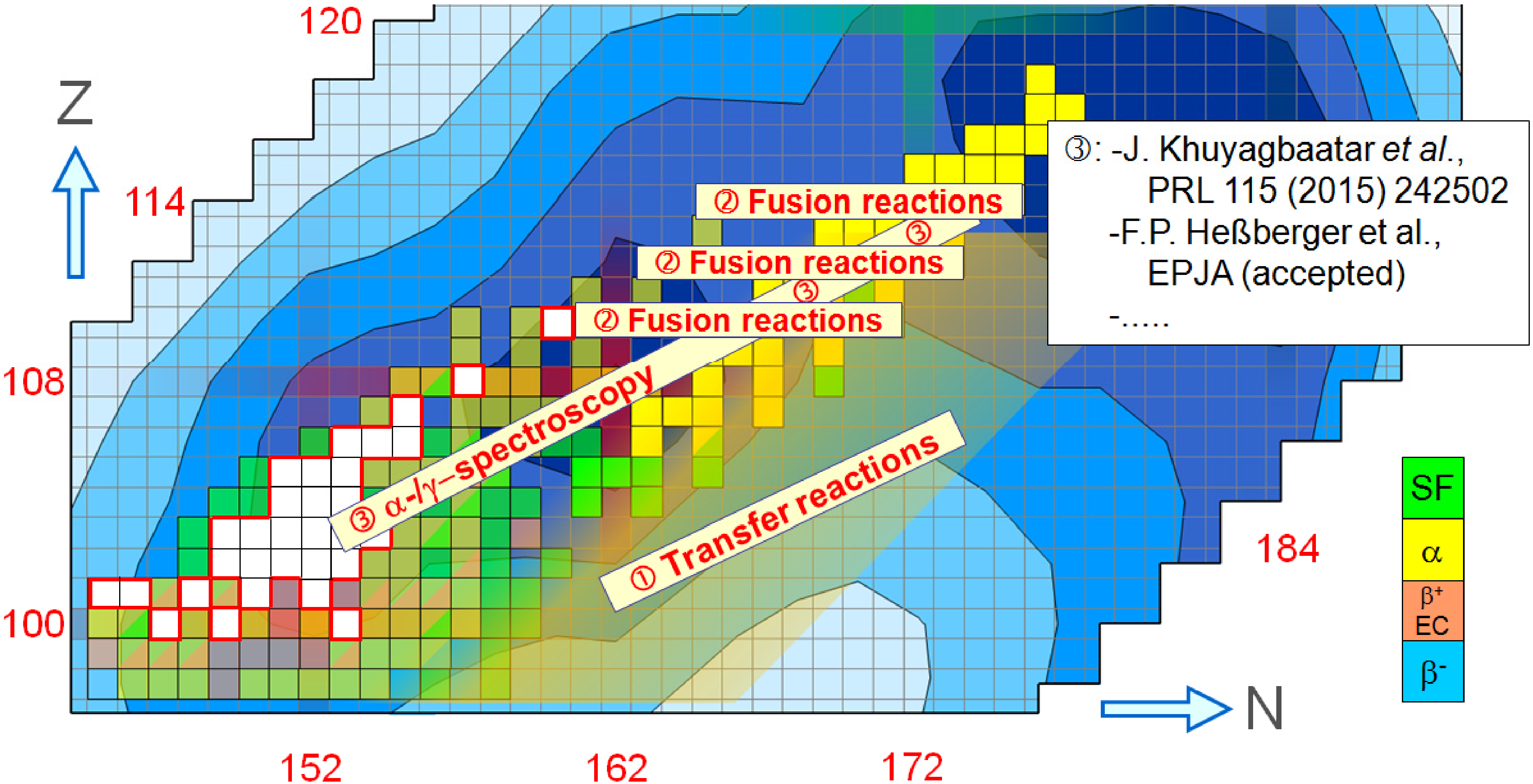
① n-rich isotopes to approach "island" center **② n-deficient isotopes: connect to mainland**



Superheavy element physics program in POF 3

Reduced GSI research program, parallel to FAIR detector tests using the "free" UNILAC beam

① n-rich isotopes to approach "island" center
② n-deficient isotopes: connect to mainland
③ nuclear structure studies up to Z ~ 114



Superheavy element physics program in POF 3

Reduced GSI research program, parallel to FAIR detector tests using the "free" UNILAC beam

① n-rich isotopes to approach "island" center
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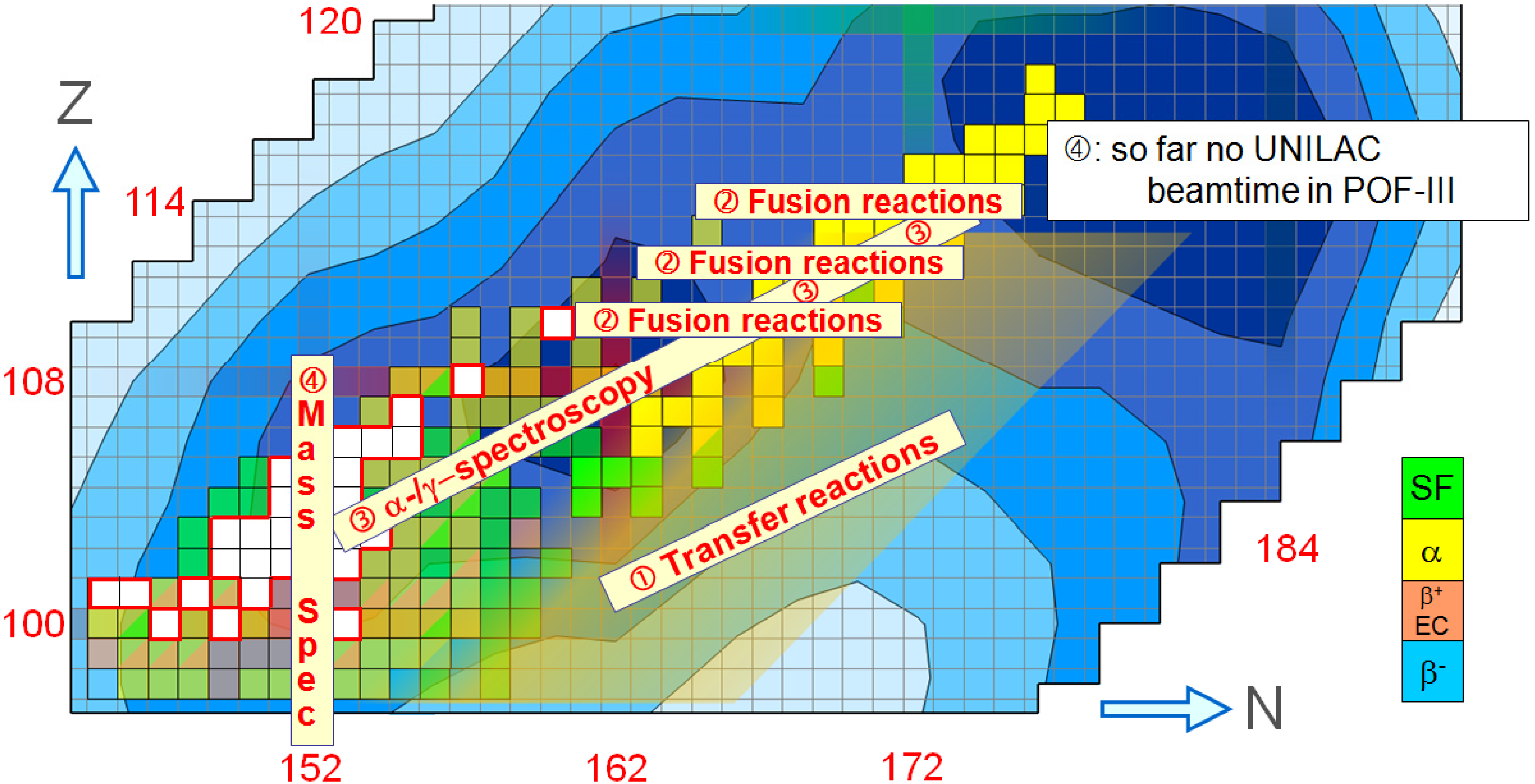
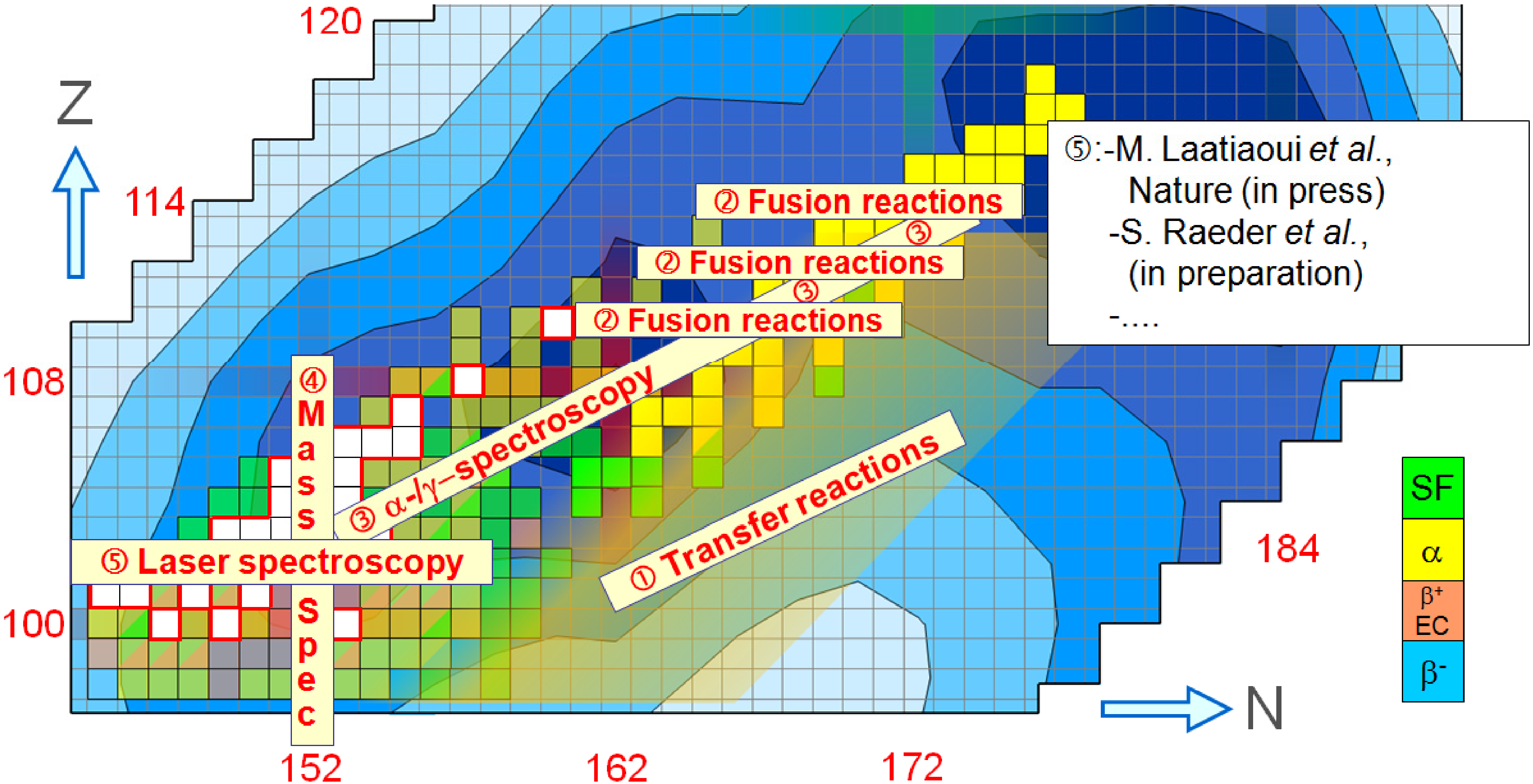
② n-deficient isotopes: connect to mainland
④ complete mapping along N=152



Superheavy element physics program in POF 3

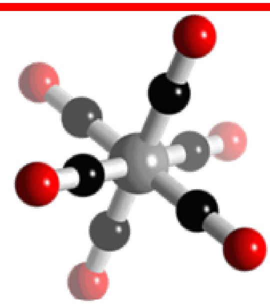
Reduced GSI research program, parallel to FAIR detector tests using the "free" UNILAC beam

① n-rich isotopes to approach "island" center
② n-deficient isotopes: connect to mainland
③ nuclear structure studies up to Z ~ 114
④ complete mapping along N=152
⑤ nobelium: atomic level studies at Z>100



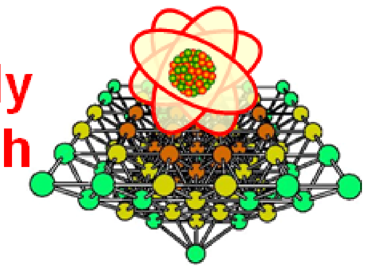
Superheavy element chemistry program in POF 3

Z~106: New single molecule chemical SHE compounds



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

Z~114: Single atom gas chromatography to study SHE-metal-bond strength



113-Au_n; Fl-Au_n

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
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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+* 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
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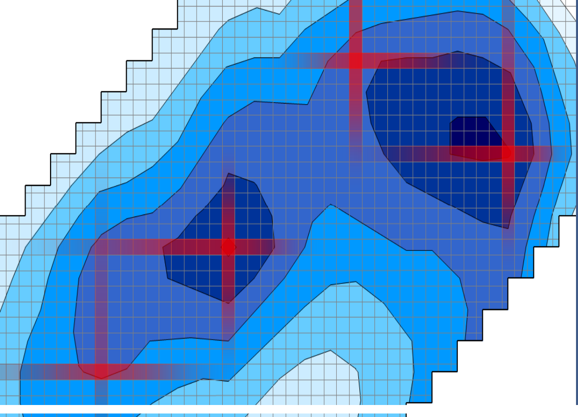
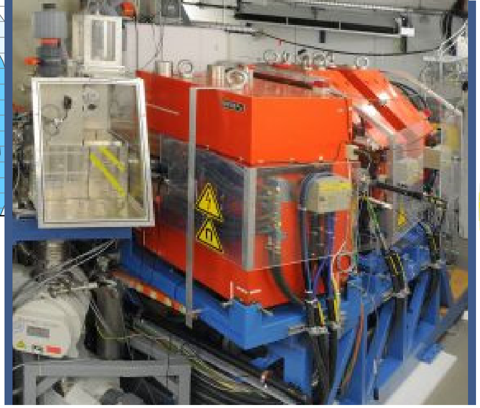
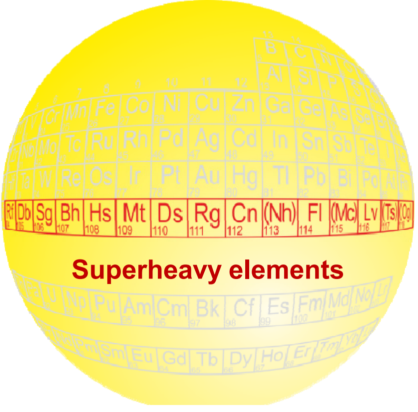
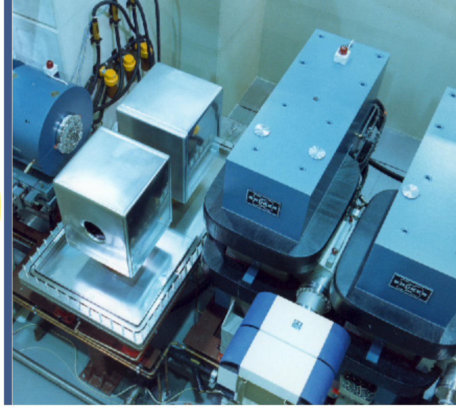
		**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

@RIKEN: **$Sg(CO)_6$ stability**: R. Eichler *et al.*
@JAEA: **$M(CO)_x$ synth.**: M. Götz, A. Yakushev *et al.*
@TRIGA MZ: **$M(CO)_x$ synth.**: V. Wolter, M. Götz *et al.*

@TASCA: **Fl** chem.: L. Lens, A. Yakushev *et al.*
@TASCA: **Nh** chem.: A. Yakushev *et al.*
@SHIP: towards **Mc**: S. Götz, S. Raeder *et al.*



UNILAC Experiments 2017+
SHE Chemistry

Christoph Düllmann

GSI
HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz

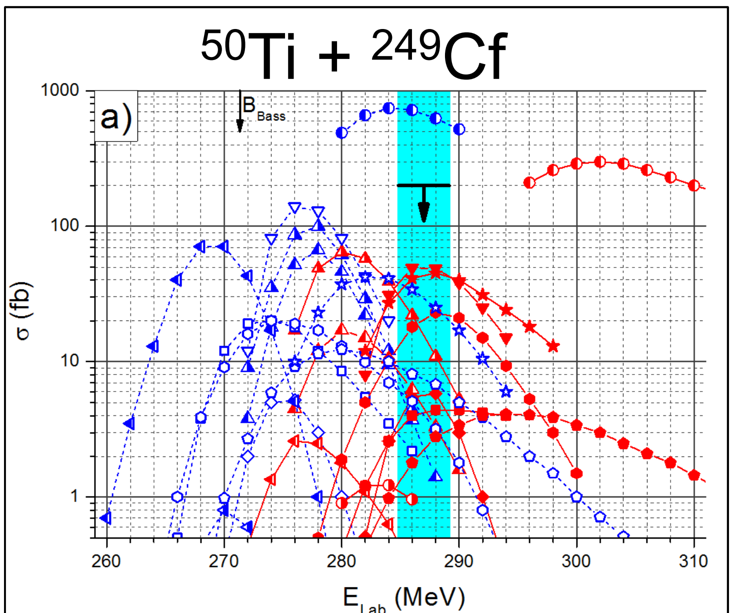
Towards new GSI elements

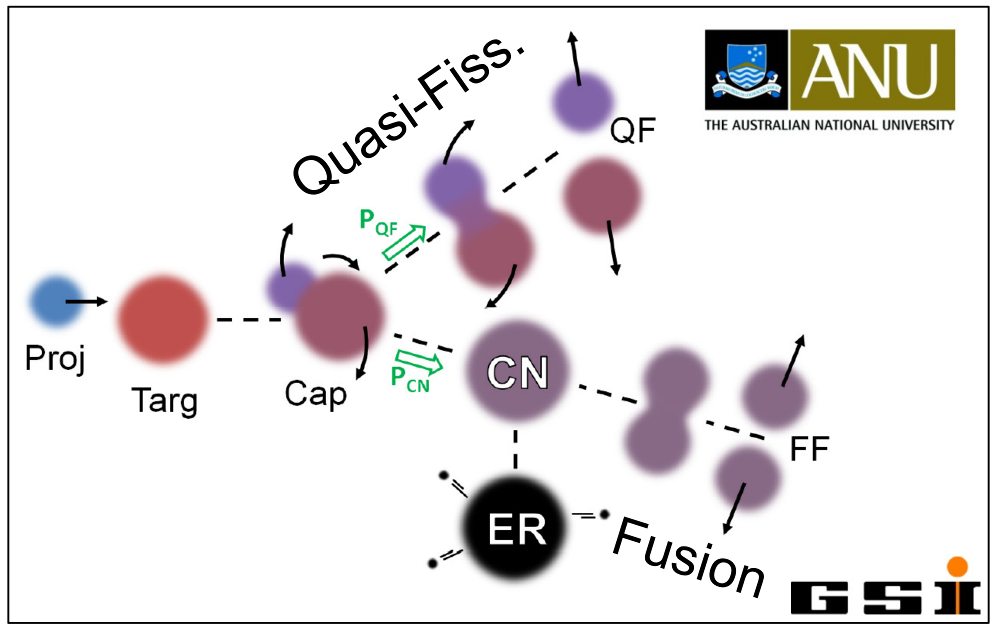
-Search experiments to resume in POF-IV; prep. studies in POF-III

World-effort to find Z>118 to date

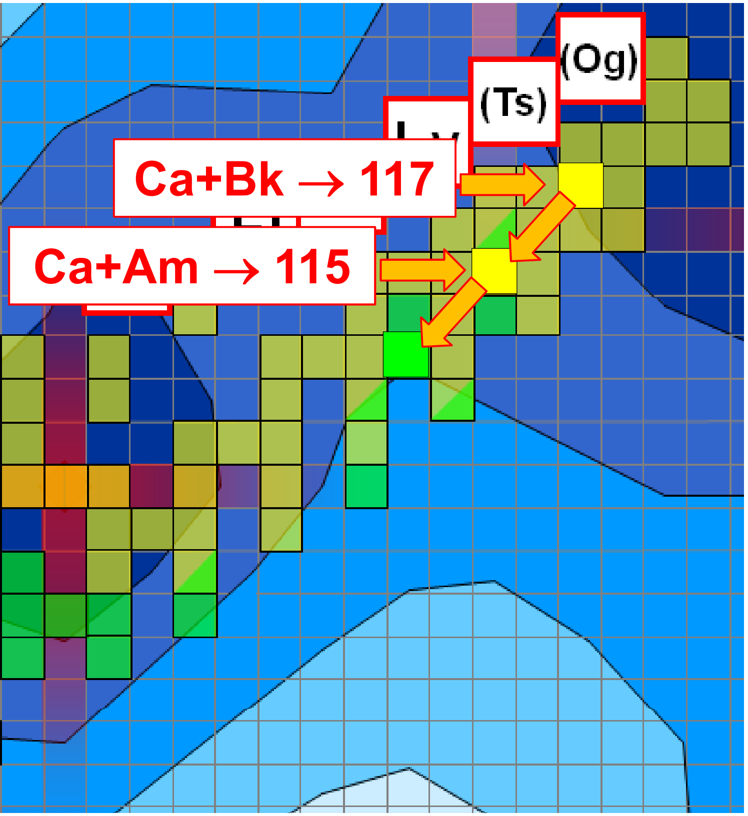
	Compound nucleus	Beamtime invested	Cross section limit[1]
$^{50}Ti + ^{249}Bk$	$^{299}119^{*}$	4.5 months	[2]
$^{64}Ni + ^{238}U$	$^{302}120^{*}$	4 months	≥90 fb
$^{58}Fe + ^{244}Pu$	$^{302}120^{*}$	2 months	≥400 fb
$^{54}Cr + ^{248}Cm$	$^{302}120^{*}$	>1 month	≥580 fb
$^{50}Ti + ^{249}Cf$	$^{299}120^{*}$	>1 month	[2]

[1] 63.2% confidence level ("one-event limit")
[2] under final analysis





Spectroscopy in the Z=114+ region



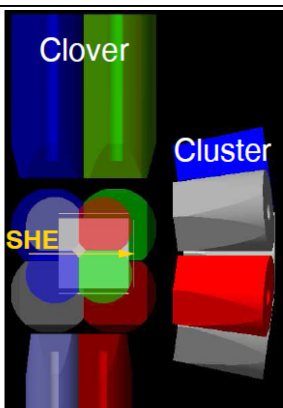
First spectroscopy around Z=114:
D. Rudolph et al., PRL 2013 (TASISpec)

Production + study of Z=115/117:
J. Khuyagbaatar et al., PRL 2014

2016: IUPAC approves 115&117

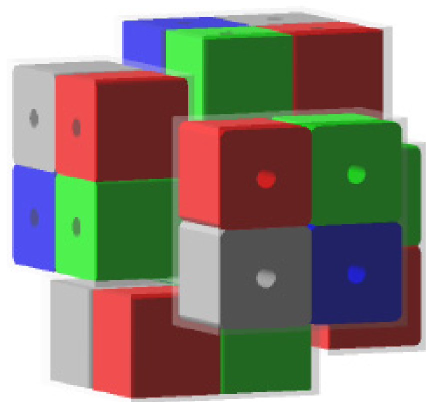
Statistical analysis (U. Forsberg et al., NPA 2016)
invalidates IUPAC (D. Rudolph et al., PLB 2016)

Identification and verification of true links w/ advanced TASISpec-setup "LUNDIUM"
(funded: Wallenberg Foundation (S); ~4.3 M€)



2012:
TASISpec

D. Rudolph,
Lund U. (S)



2017+:
LUNDIUM

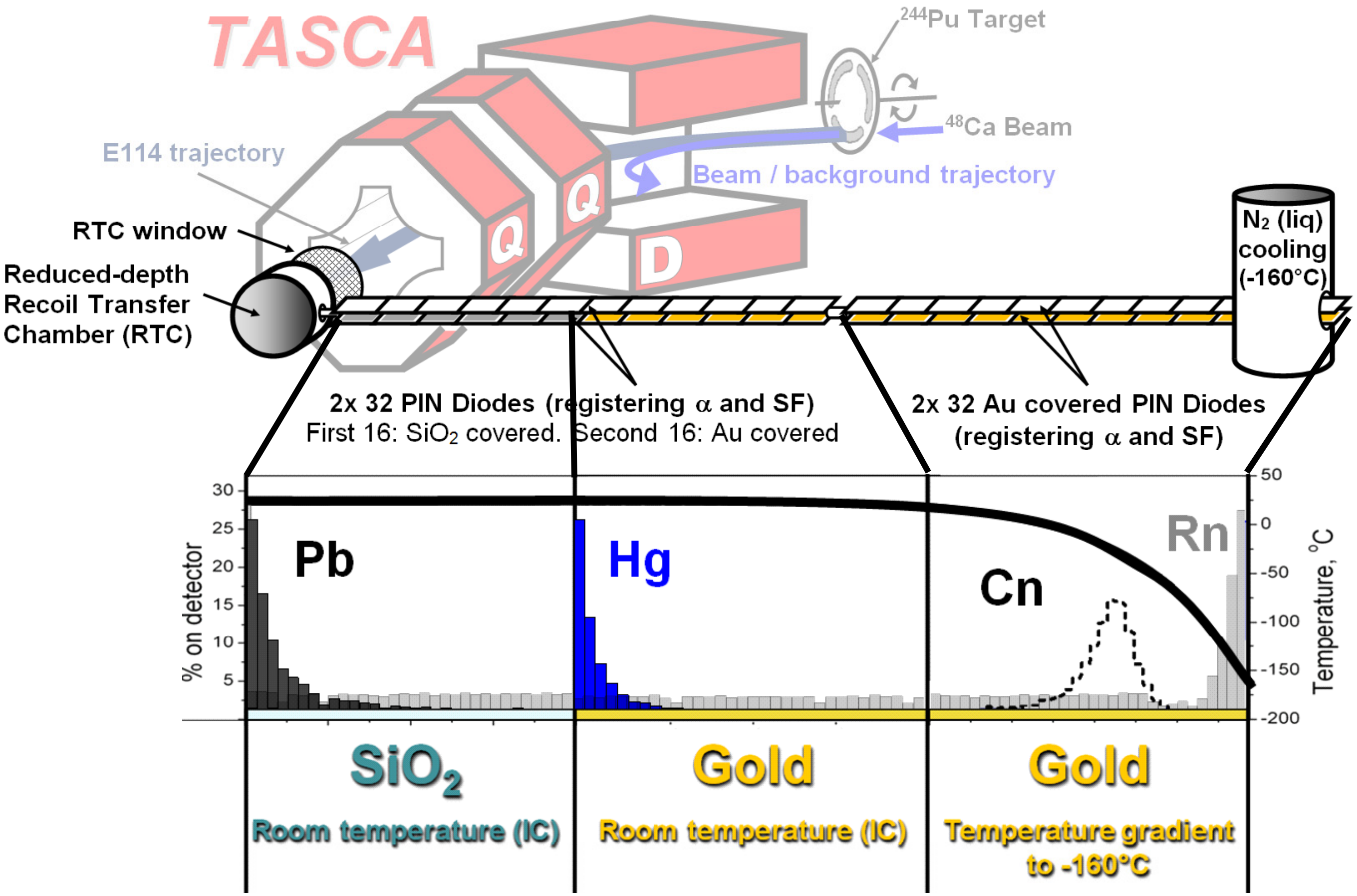
D. Rudolph,
Lund U. (S)

LUND UNIVERSITY

Nh, Fl, Mc... single atom chemistry

Bundesministerium für Bildung und Forschung

Study interaction of Fl with SiO_2 / Au (room temperature) / Au (temp. gradient)



Fl (Z=114): 8 atoms observed, final analysis ongoing (PhD thesis L. Lens). ✓

Nh (Z=113): 1st exp. done, 0 events, under analysis ☞

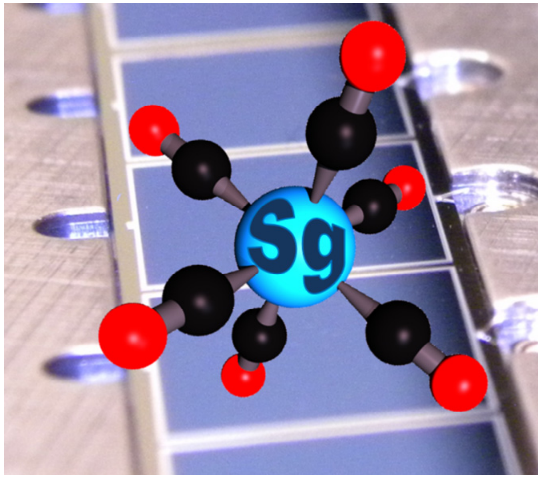
Mc+ (Z=115+): More short-lived, needs faster setup. Coupling of chemistry to SHIP buffer gas cell under construction (PhD thesis S. Götz) ☞

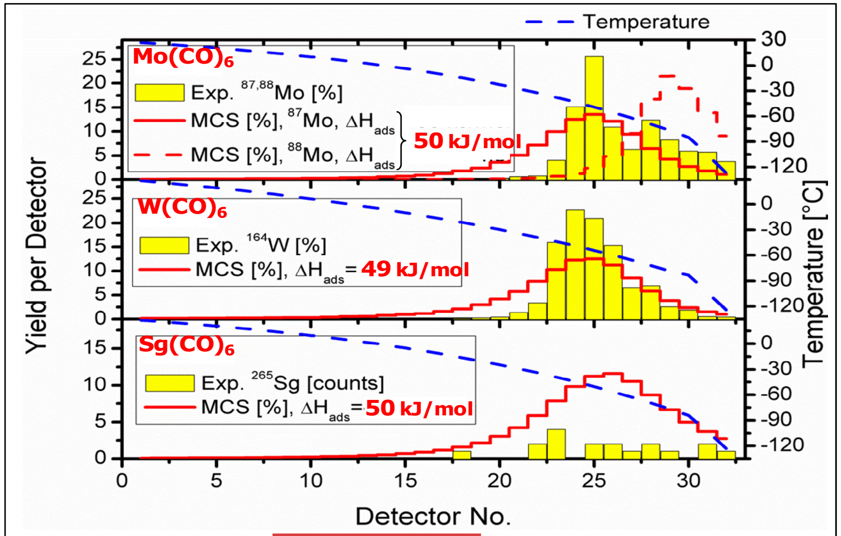
New SHE compound classes for SHE spectroscopy

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

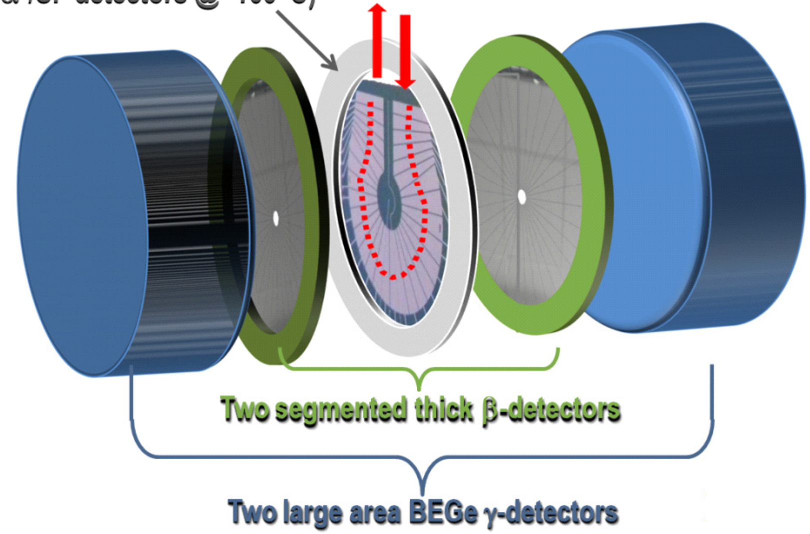
Hexacarbonyls: $Mo(CO)_6$ / $W(CO)_6$ / $Sg(CO)_6$

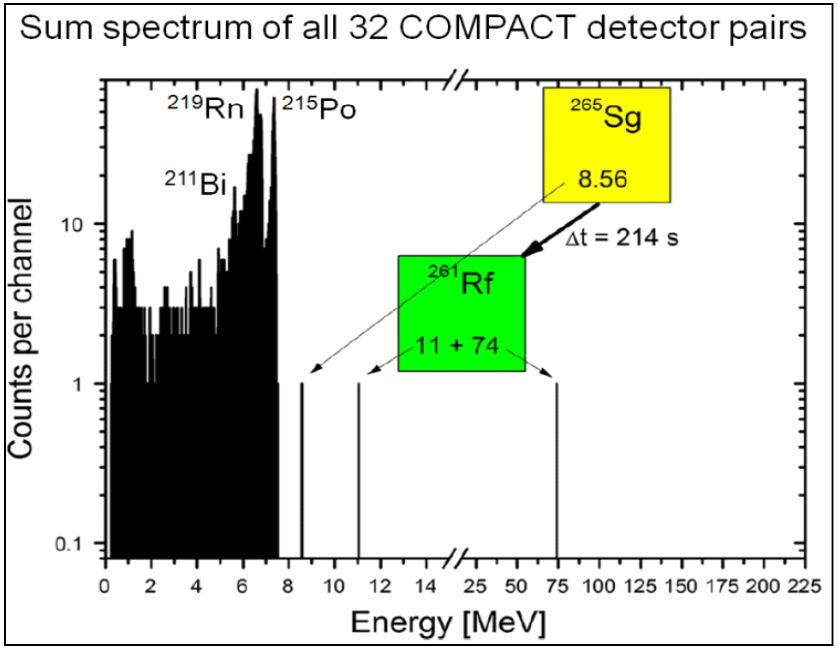


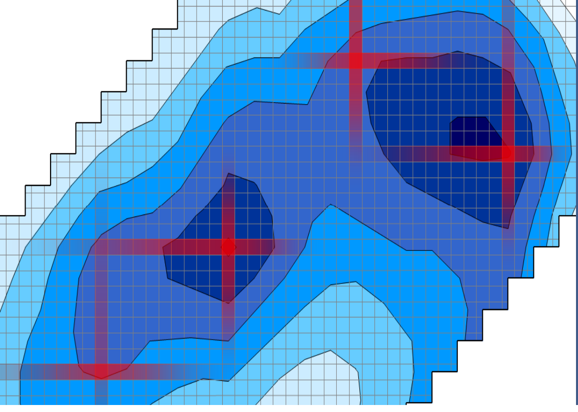
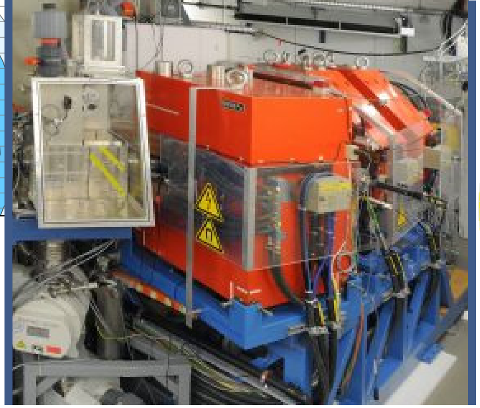
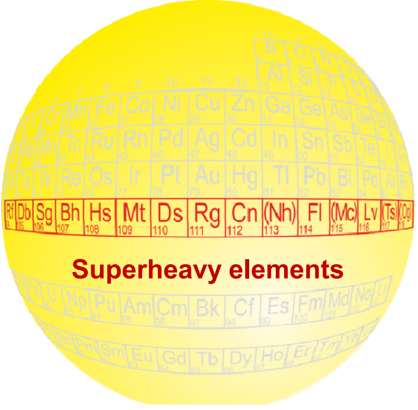


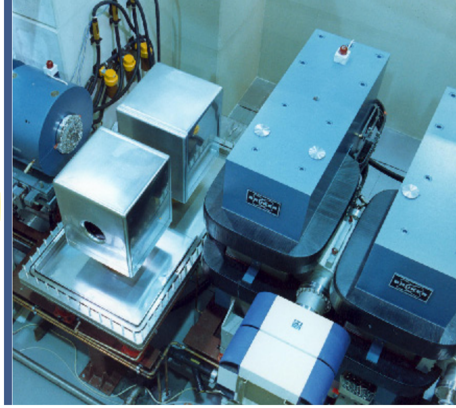
J. Even *et al.* Science 345 (2014) 1491

ALBEGA





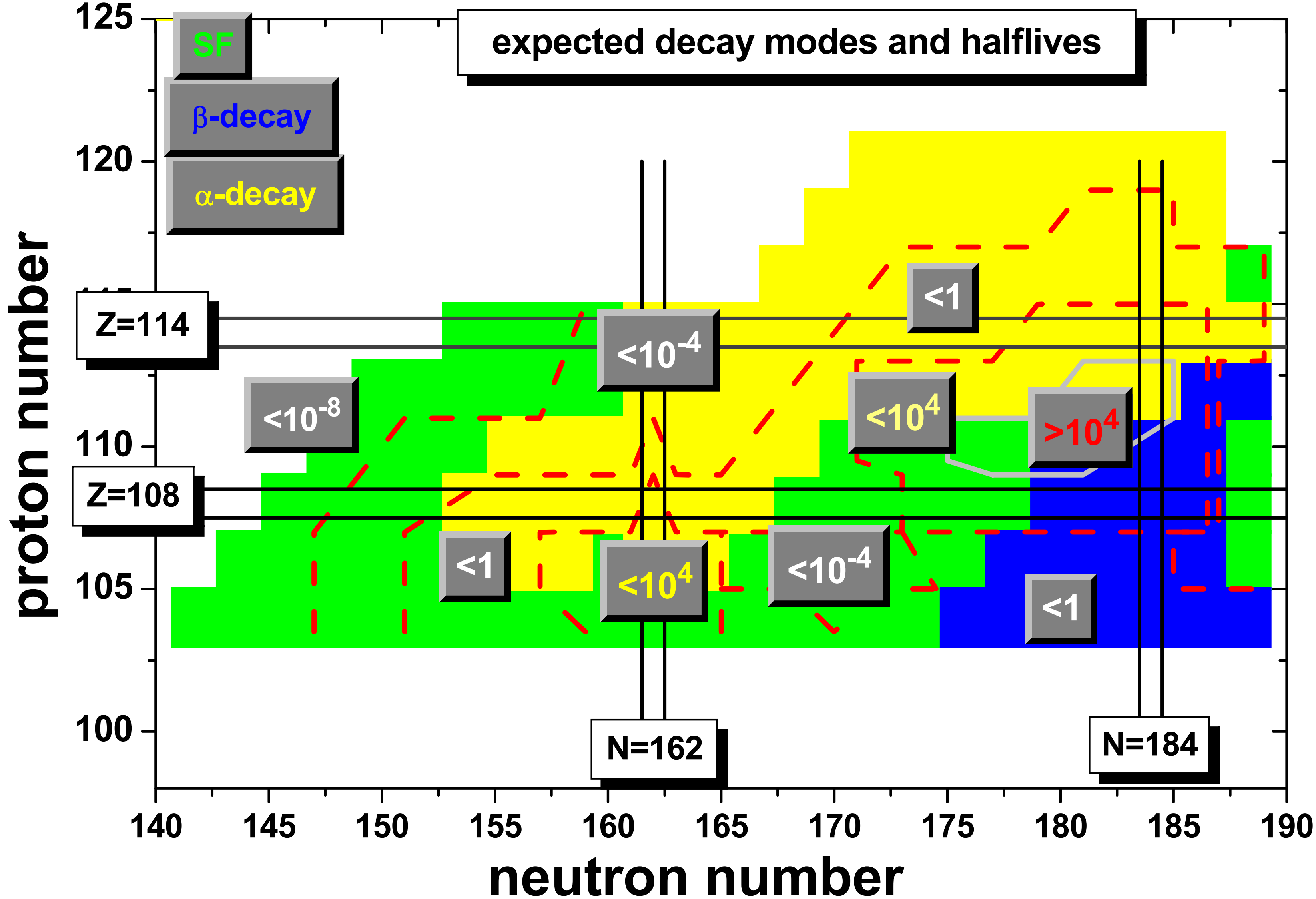






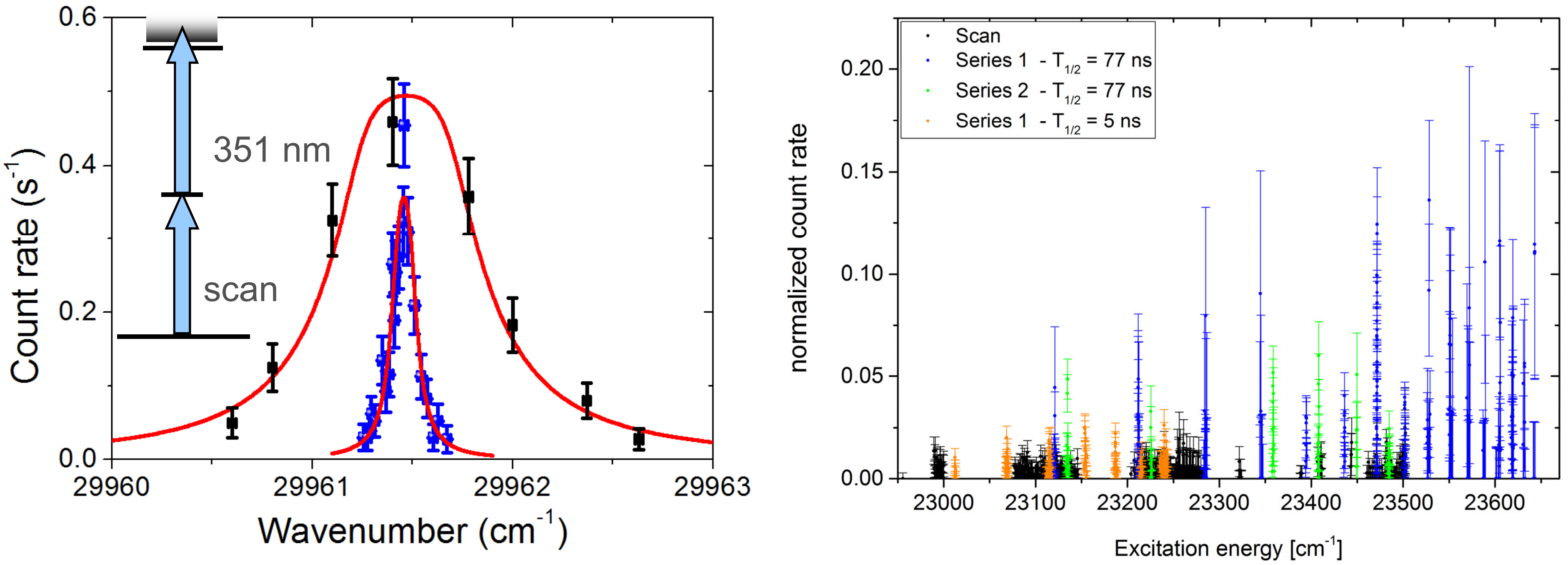
UNILAC Experiments 2017+
SHE Physics

Michael Block

Expected Decay Modes and Half-lives of SHN



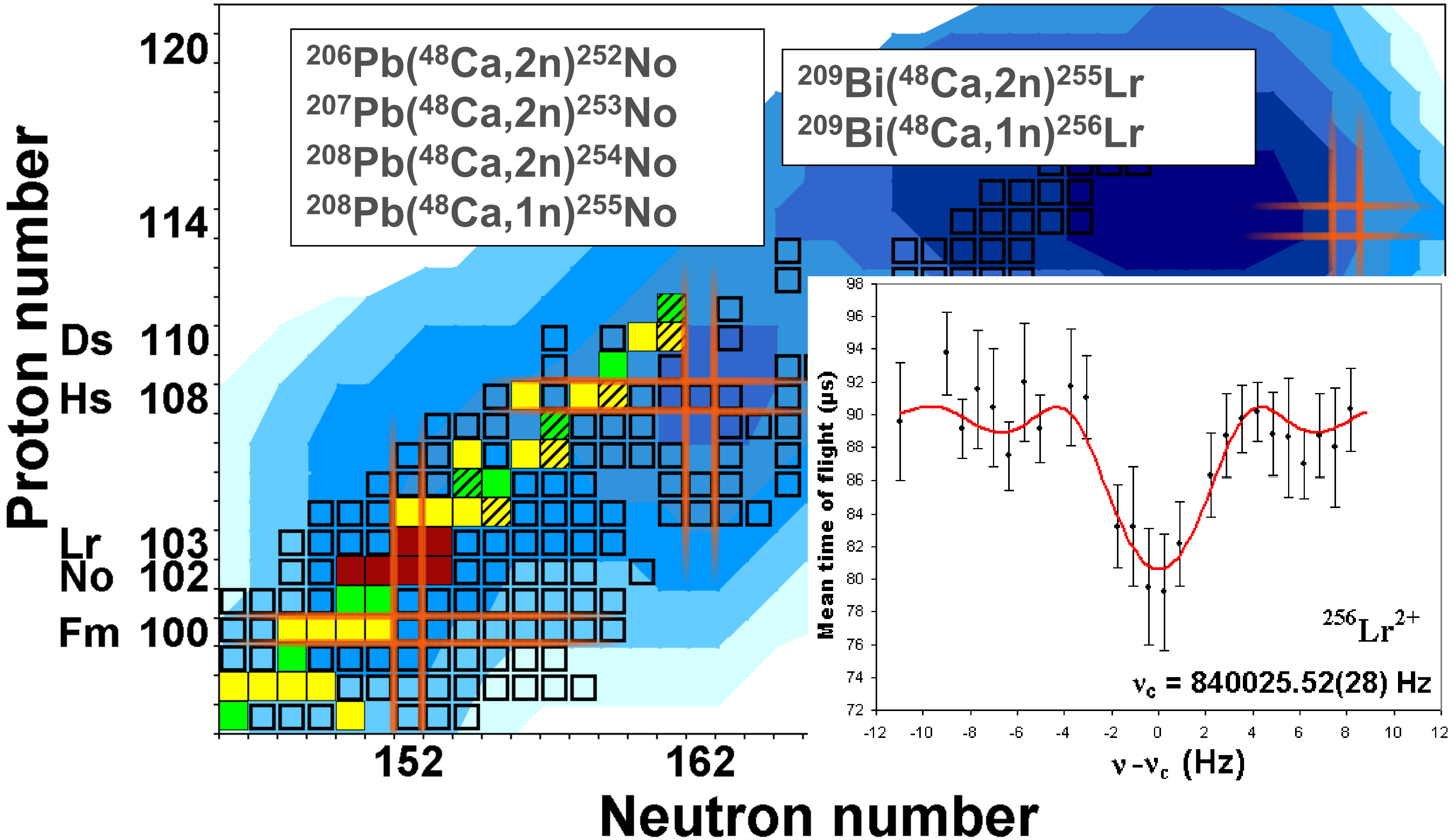
Search for Atomic States in Nobelium



- Several atomic states identified in nobelium isotopes $^{252\text{-}254}$No by laser resonance ionization spectroscopy in 2015/2016 beamtimes
- Hyperfine splitting in 253No and isotope shift give access to spin, moments
- First ionization potential of nobelium determined via Rydberg series

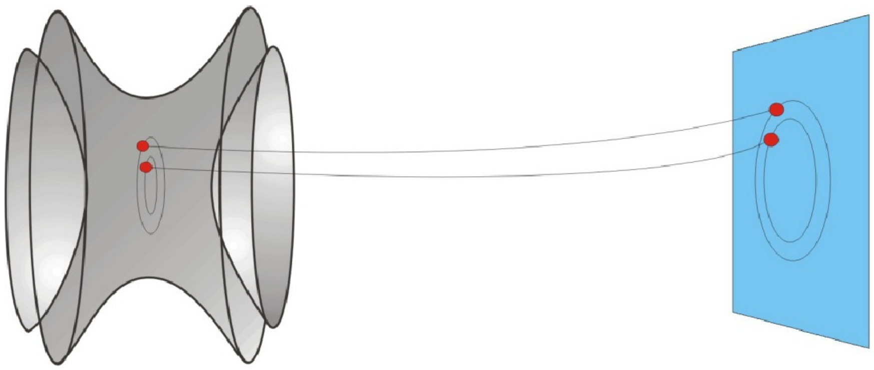
Part of 2015 results: M. Laatiaoui et al., Nature in press

Direct mass measurements with SHIPTRAP

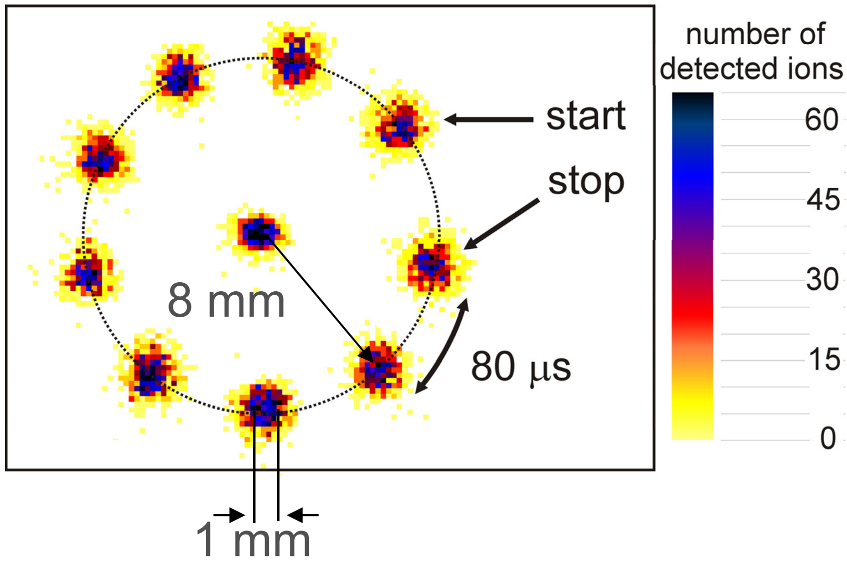


M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

Recent Breakthrough in Mass Spectrometry



Spatially resolved detection



nature COMMUNICATIONS

ARTICLE

Received 29 May 2015 | Accepted 19 Nov 2015 | Published 18 Jan 2016 DOI: 10.1038/ncomms10246 OPEN

Isotope dependence of the Zeeman effect in lithium-like calcium

Florian Köhler[1,2], Klaus Blaum[2], Michael Block[1,3,4], Stanislav Chenmarev[2,5], Sergey Eliseev[2], Dmitry A. Glazov[5,6,7], Mikhail Goncharov[2], Jiamin Hou[2], Anke Kracke[2], Dmitri A. Nesterenko[8], Yuri N. Novikov[2,5,8], Wolfgang Quint[1], Enrique Minaya Ramirez[2], Vladimir M. Shabaev[5], Sven Sturm[2], Andrey V. Volotka[5,6] & Günter Werth[9]

PRL 115, 062501 (2015) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2015

Direct Measurement of the Mass Difference of ^{163}Ho and ^{163}Dy Solves the Q-Value Puzzle for the Neutrino Mass Determination

S. Eliseev,[1] K. Blaum,[1] M. Block,[2,3,4] S. Chenmarev,[1,5] H. Dorrer,[4,6,7] Ch. E. Düllmann,[2,3,4,8] C. Enss,[9] P. E. Filianin,[1,5] L. Gastaldo,[9] M. Goncharov,[1] U. Köster,[10] F. Lautenschläger,[2] Yu. N. Novikov,[1,5,11] A. Rischka,[1] R. X. Schüssler,[1] L. Schweikhard,[12] and A. Türler[6,7]

[1]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany*
[3]*Helmholtz-Institut Mainz, 55099 Mainz, Germany*
[4]*Institut für Kernchemie, Johannes Gutenberg-Universität, 55128 Mainz, Germany*
[5]*Physics Faculty of St.Petersburg State University, 198904 Peterhof, Russia*
[6]*Paul Scherrer Institute, 5232 Villigen, Switzerland*
[7]*Universität Bern, 3012 Bern, Switzerland*
[8]*PRISMA Cluster of Excellence, Johannes Gutenberg-Universität, 55099 Mainz, Germany*
[9]*Kirchhoff Institut für Physik, Heidelberg Universität, INF 227, 69120 Heidelberg, Germany*
[10]*Institut Laue-Langevin, 38042 Grenoble, France*
[11]*Petersburg Nuclear Physics Institute, Gatchina, 188300 St. Petersburg, Russia*
[12]*Institut für Physik, Ernst-Moritz-Arndt-Universität, 17487 Greifswald, Germany*

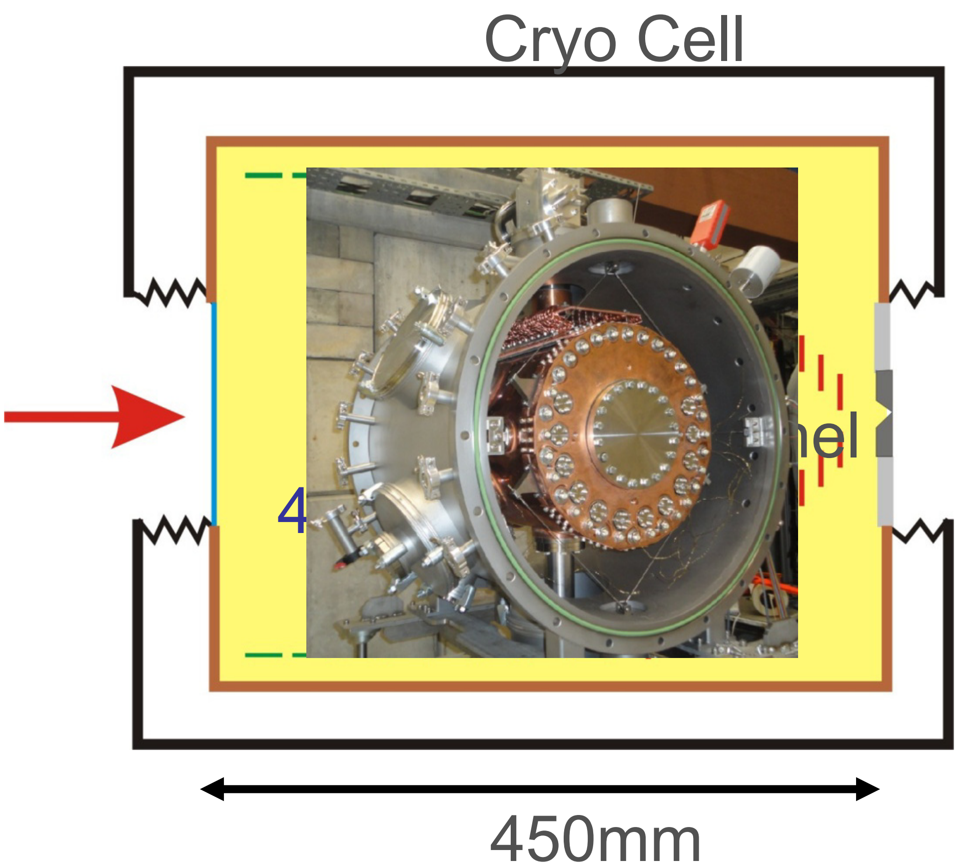
(Received 19 May 2015; published 5 August 2015)

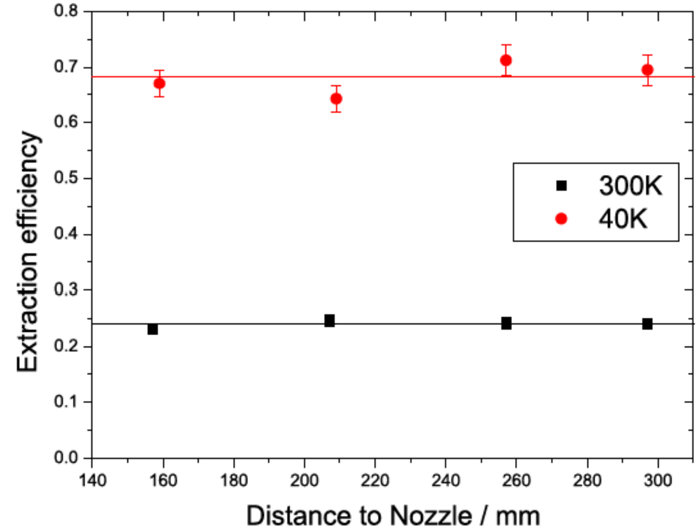
The atomic mass difference of ^{163}Ho and ^{163}Dy has been directly measured with the Penning-trap mass spectrometer SHIPTRAP applying the novel phase-imaging ion-cyclotron-resonance technique. Our measurement has solved the long-standing problem of large discrepancies in the Q value of the electron capture in ^{163}Ho determined by different techniques. Our measured mass difference shifts the current Q value of 2555(16) eV evaluated in the Atomic Mass Evaluation 2012 [G. Audi *et al.*, Chin. Phys. C 36, 1157 (2012)] by more than 7σ to $2833(30_{stat})(15_{sys})\ eV/c^2$. With the new mass difference it will be possible, e.g., to reach in the first phase of the ECHo experiment a statistical sensitivity to the neutrino mass below 10 eV, which will reduce its present upper limit by more than an order of magnitude.

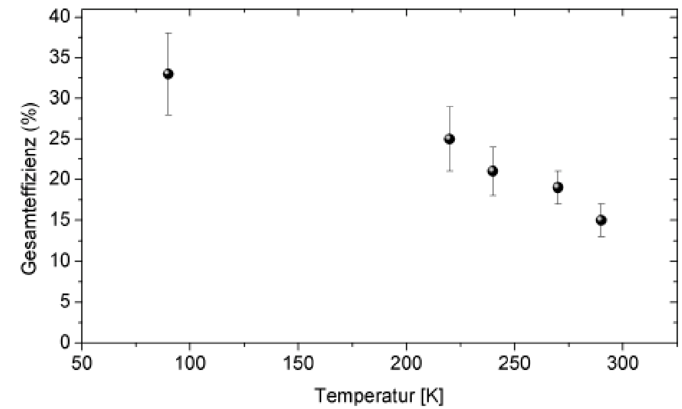
DOI: 10.1103/PhysRevLett.115.062501 PACS numbers: 23.40.-s, 07.75.+h, 14.60.Lm, 37.10.Ty

S. Eliseev et al., Phys. Brev. Lett., 105 (2013) 062501
S. Eliseev et al., Appl. Phys. B114, 107 (2014)
S. Eliseev et al., Phys. Rev. Lett. 115 (2015) 062501

Cryogenic Gas Cell Commissioning



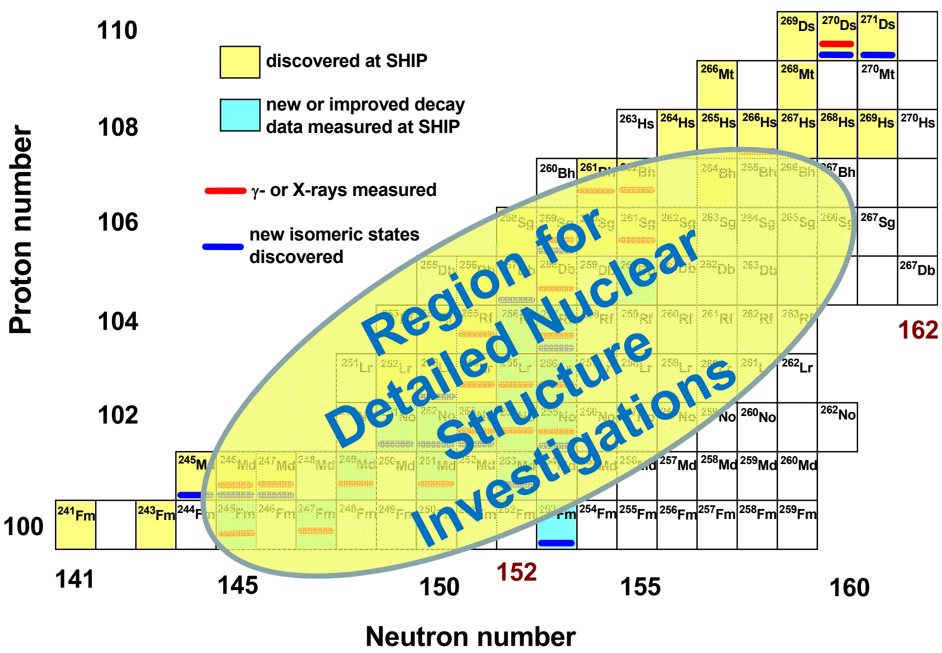




- Larger stopping volume and coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Efficiency increased by at least a factor of 4 compared to old gas cell

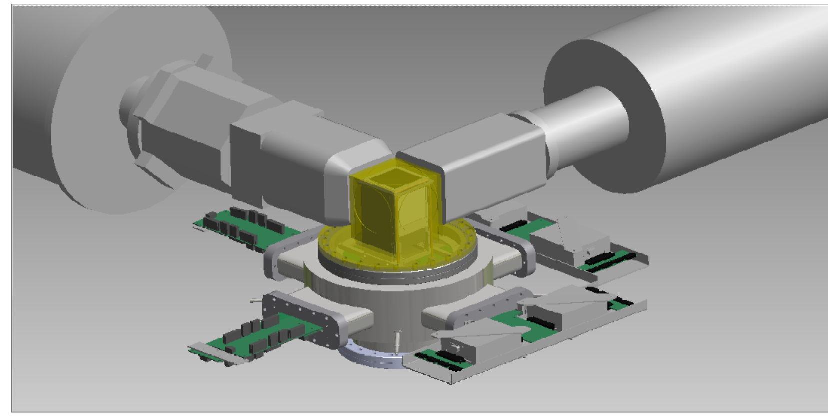
C. Droese et al. NIM B 338, 126 (2014), O. Kaleja, Master Thesis TU Darmstadt (2016)

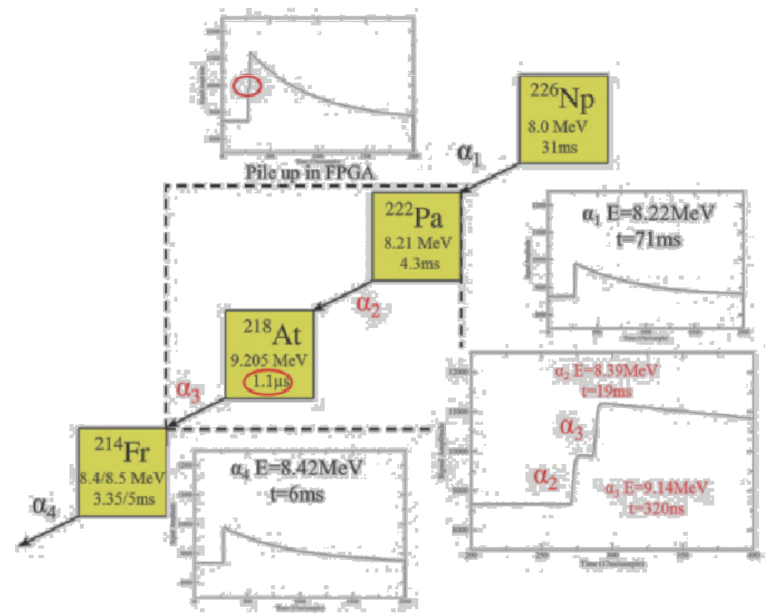
Nuclear spectroscopy of SHN at SHIP



New SHIP Focal Plane Detector System with digital data processing

✓ successfully commissioned in 2015/2016





particle (α, CE) – γ – spectroscopy

- Investigate strength and location of proton and neutron shells
- study isomeric states (K isomers)
- determine spontaneous fission properties
- challenge theoretical models

Beam requirements for POF-III (until 2020)

UNILAC beamtime: 50 Hz / 5 ms
Beamtime ~10-30 days per experiment

No search for new elements

Main projectiles:
^{22}Ne, ^{48}Ca (ECR), ^{50}Ti (ECR/PIG)

Energies:
up to 6 MeV/u, flexible energy selection in interval 4-6 MeV/u
Intensities: 1 $\mu A_{particle}$ (DC) on target

Parasitic beamtimes (5 Hz / 5 ms) für methods development and preparatory experiments

Beam requirements for POF-IV (2021+)

UNILAC beamtime: 50 Hz / 5 ms
100 days p.a. for experiments up to Z=118

cw-Linac: 100% duty cycle
Longer beamtimes, also for search beyond Z=118

Typical projectiles:
^{22}Ne, ^{23}Na, ^{26}Mg, ^{36}S, ^{40,44,48}Ca, ^{50}Ti, ^{50,54}Cr, ^{51}V, ^{64}Ni, ^{136}Xe, ^{238}U

Energies:
up to 6 MeV/u, flexible energy selection in interval 4-6 MeV/u

Intensities:
>1 $\mu A_{particle}$ (DC) on target

Parasitic beamtimes (5 Hz / 5 ms) für methods development and preparatory experiments