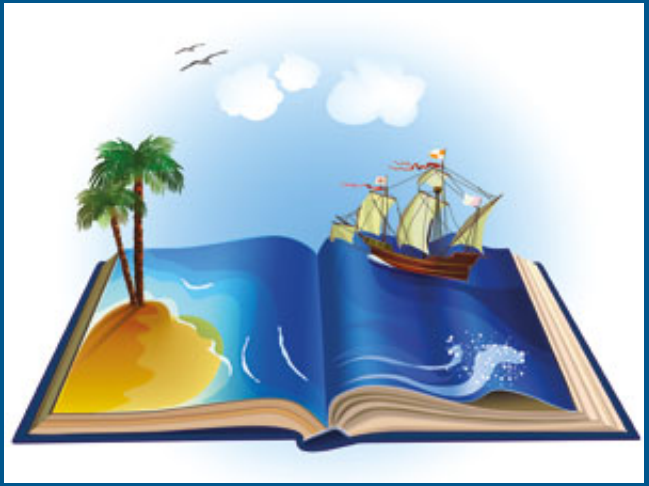
INT Workshop Seattle 2013

Superheavy Element Research at GSI
A Selection of Recent Results



Michael Block

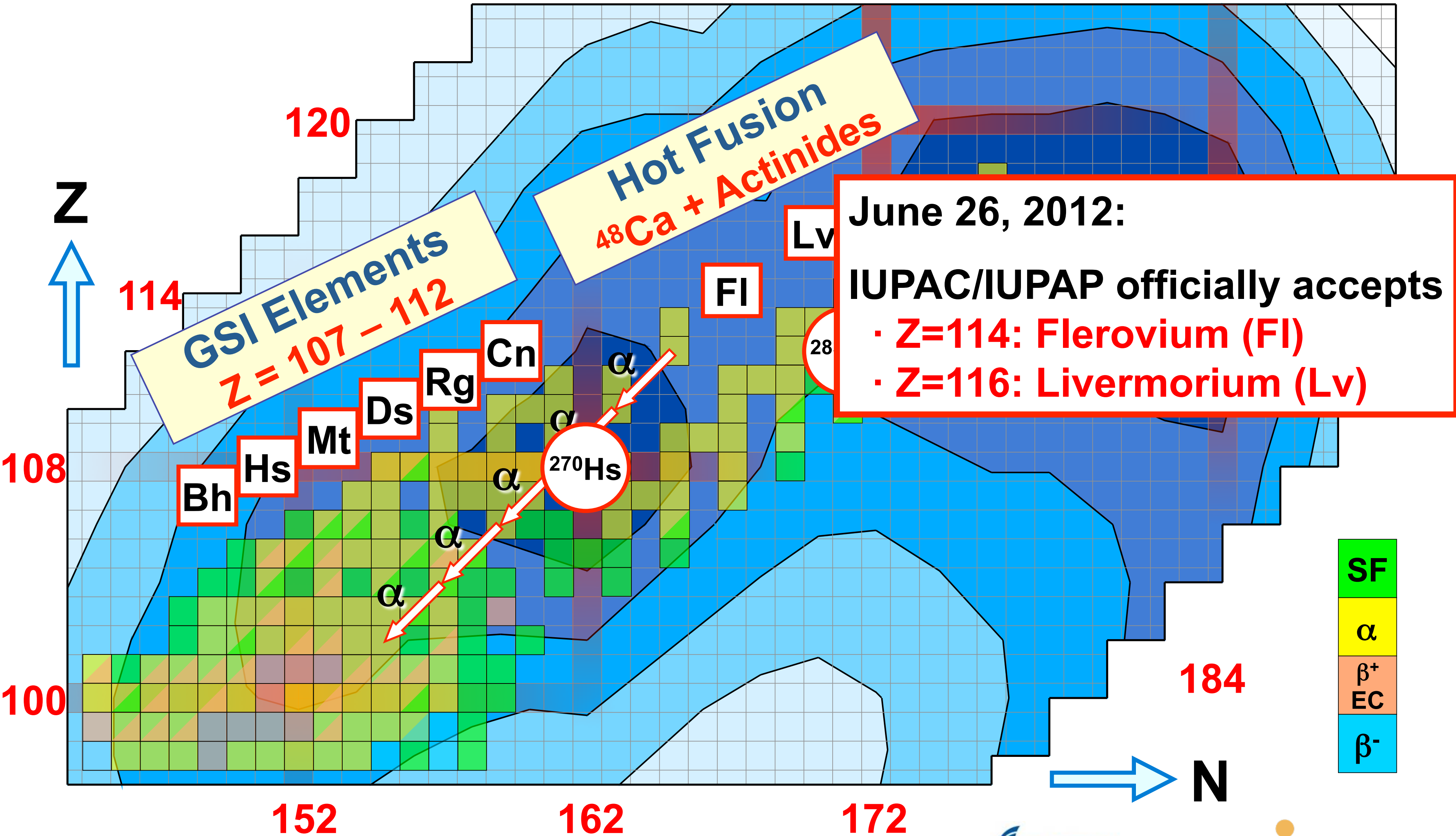
with contributions by

Chris Düllmann, Fritz Hessberger, Dirk Rudolph

HELMHOLTZ Institut Mainz

HELMHOLTZ ASSOCIATION GSI

Superheavy Elements – Current Status

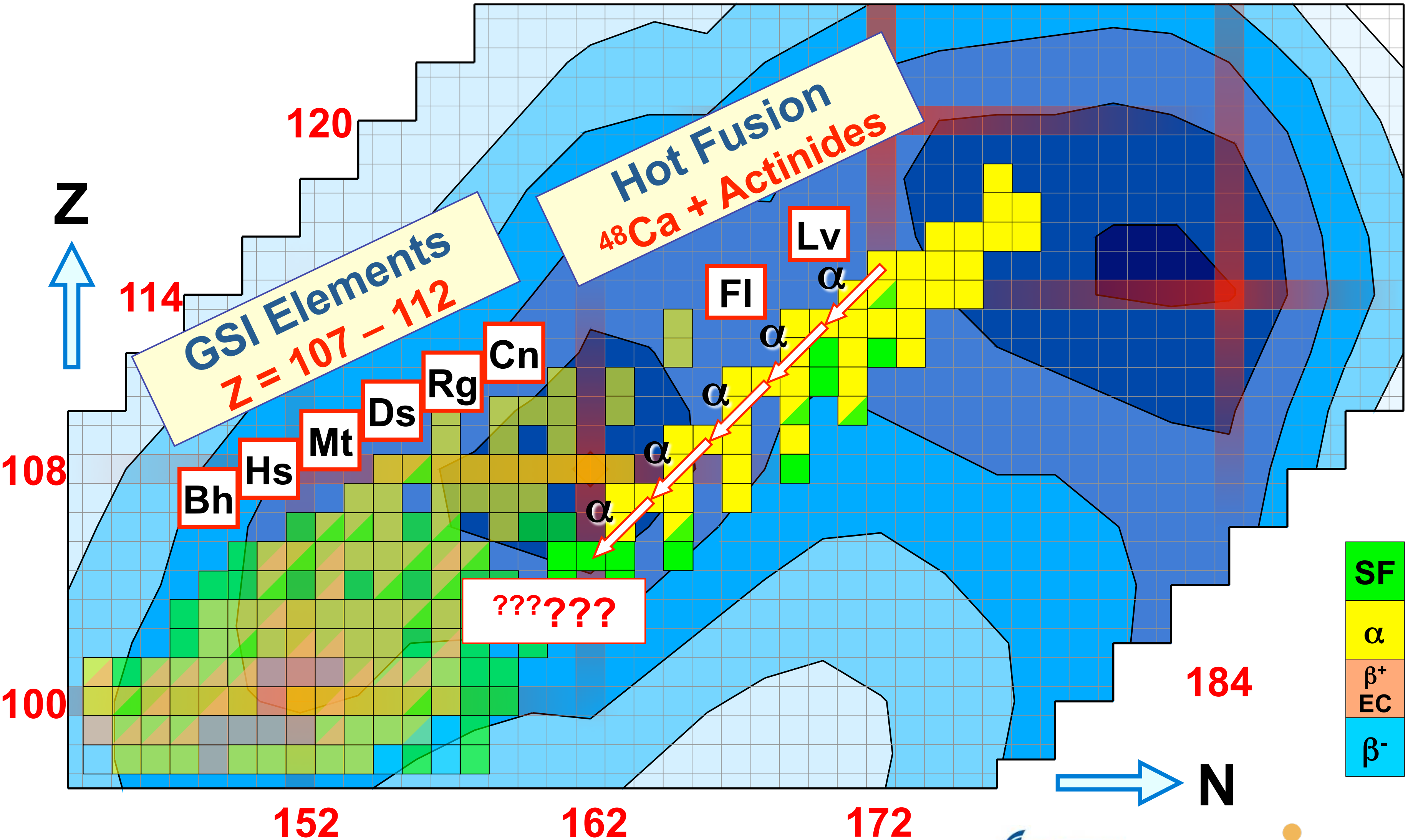


June 26, 2012:

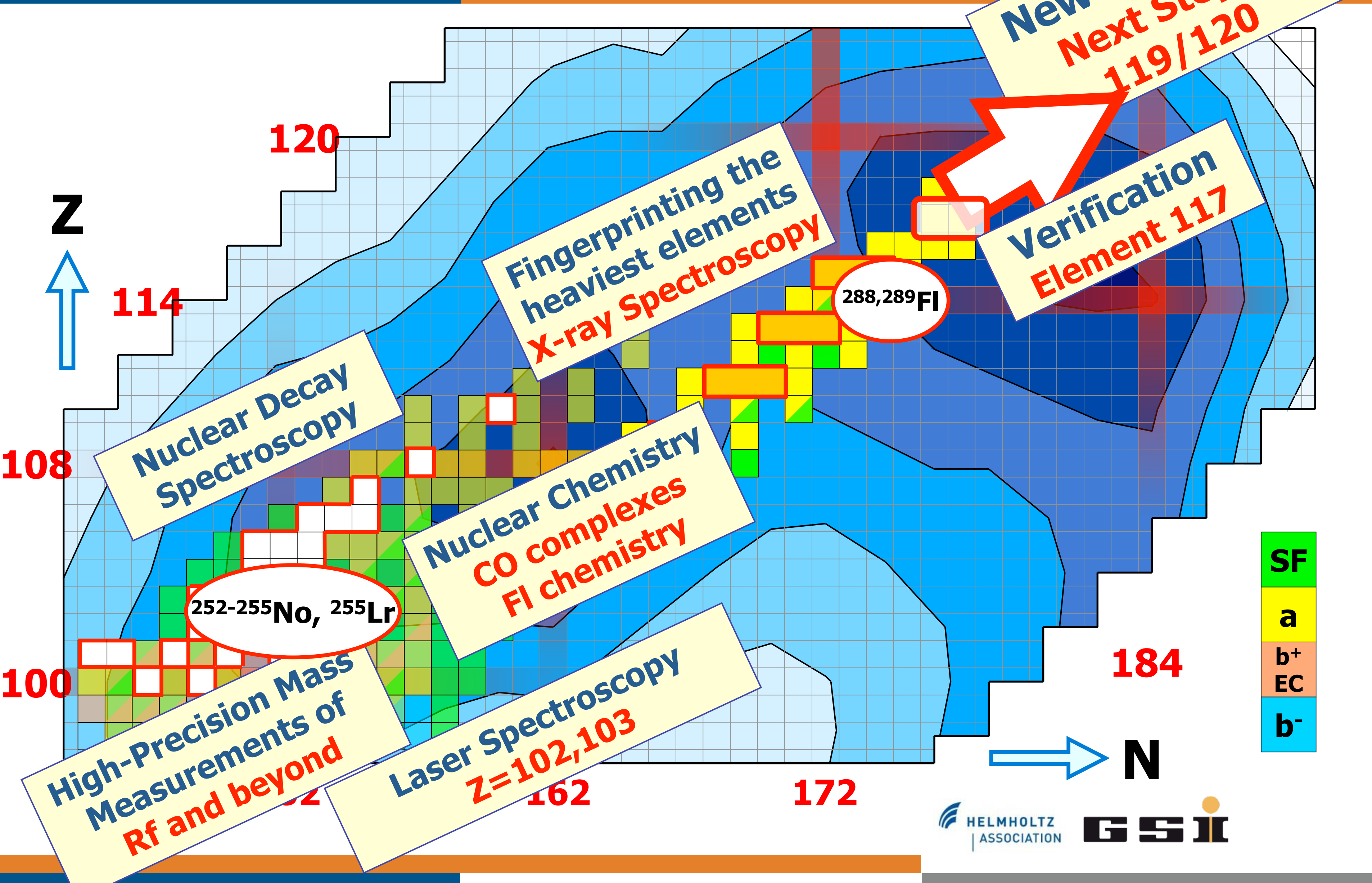
IUPAC/IUPAP officially accepts

- **Z=114: Flerovium (Fl)**
- **Z=116: Livermorium (Lv)**

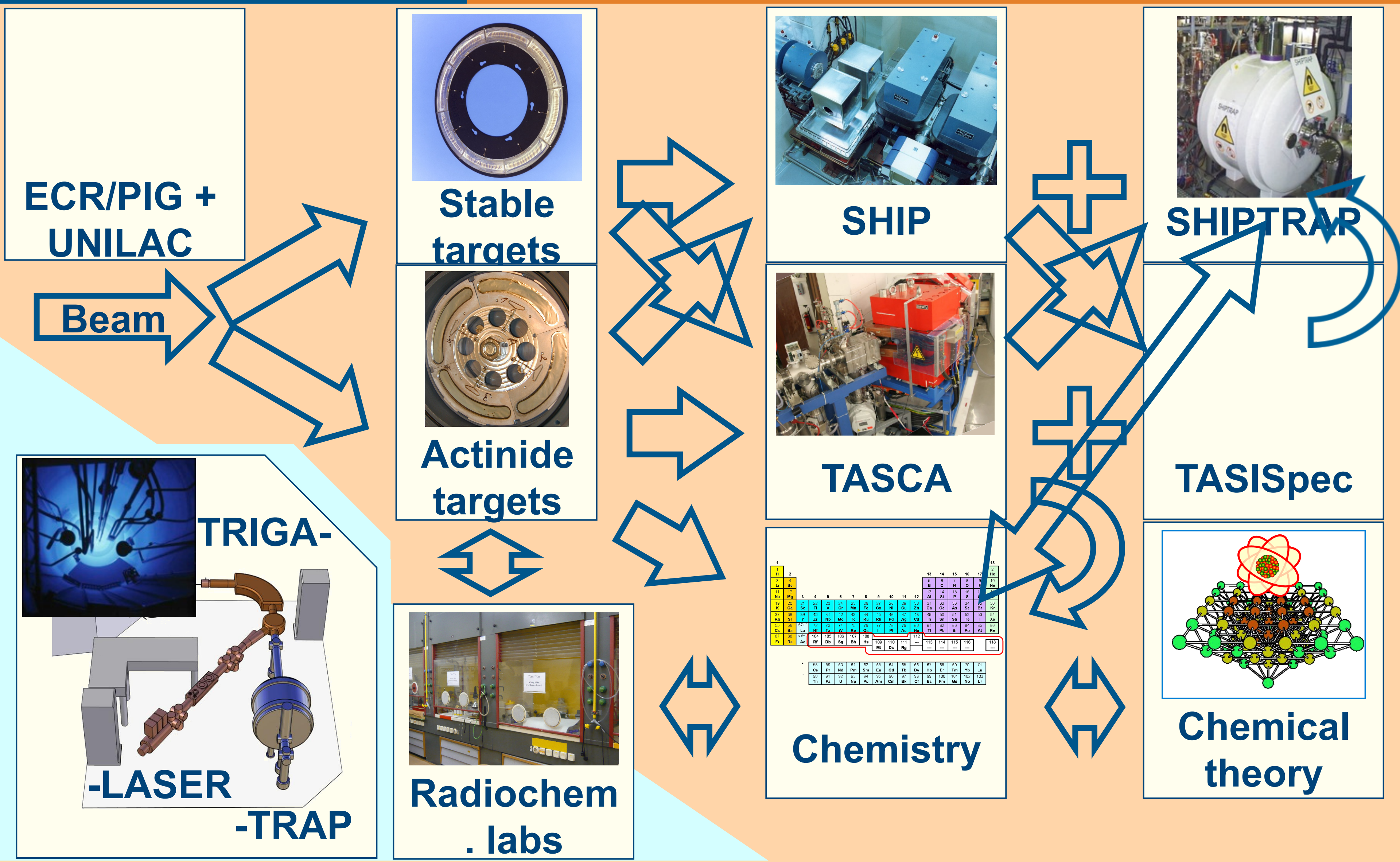
Superheavy Elements – Current Status



Superheavy Elements – The hottest Topics



Unique Combination for SHE Studies



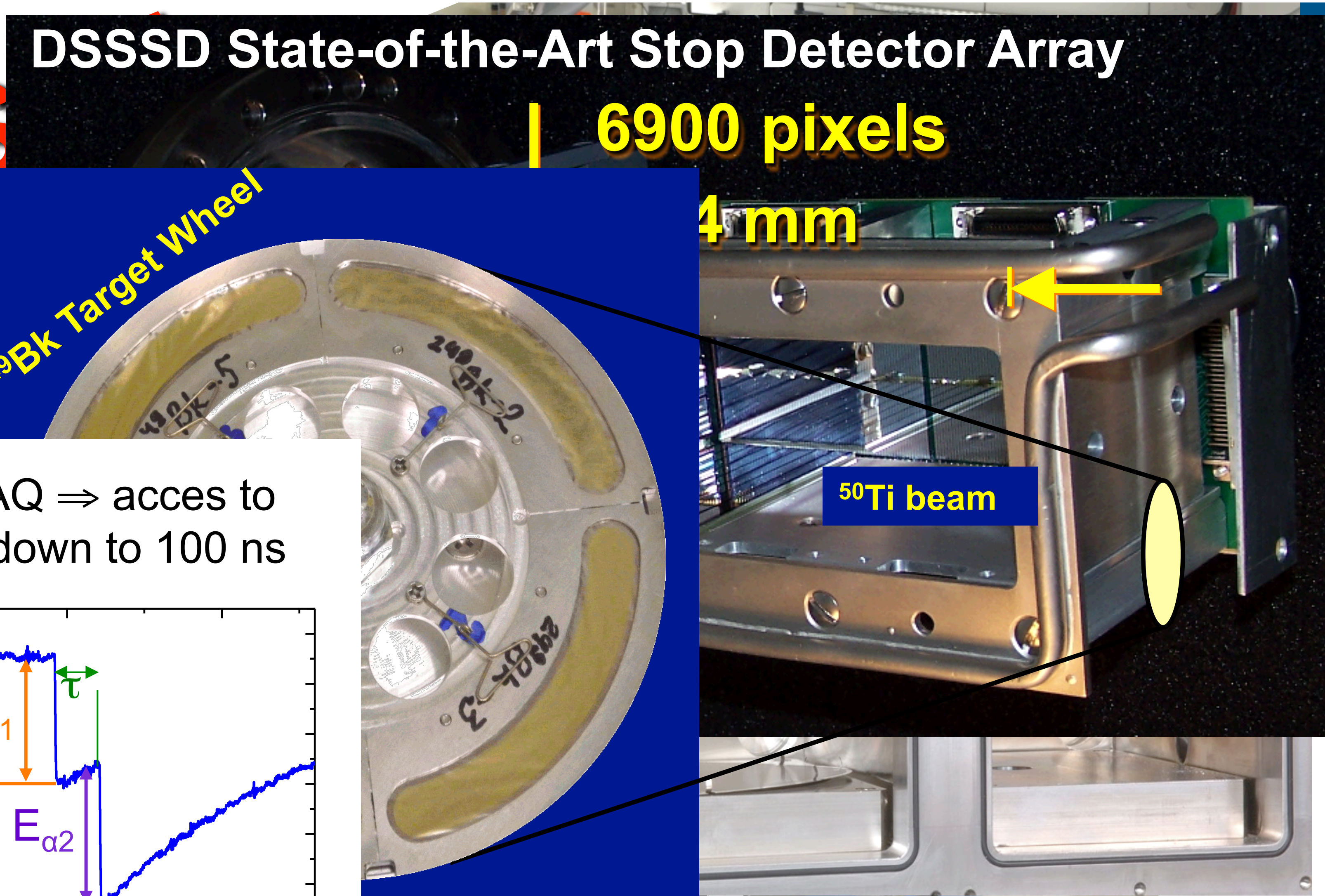
Courtesy Ch.E. Düllmann

The *TASCA* Collaboration

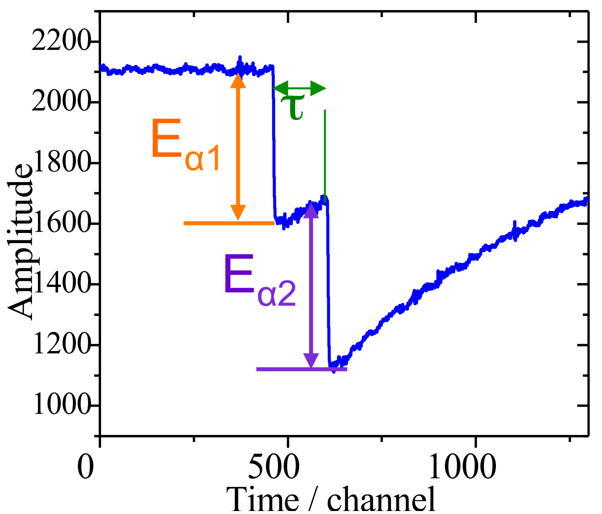
ANU Canberra (Australia)
LBNL/UCB Berkeley (USA)
LLNL Livermore (USA)
Vanderbilt U (USA)
ORNL Oak Ridge (USA)
U Liverpool (UK)
U Surrey (UK)
U Lund (Sweden)

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)

DSSSD State-of-the-Art Stop Detector Array



Digital DAQ ⇒ acces to lifetimes down to 100 ns

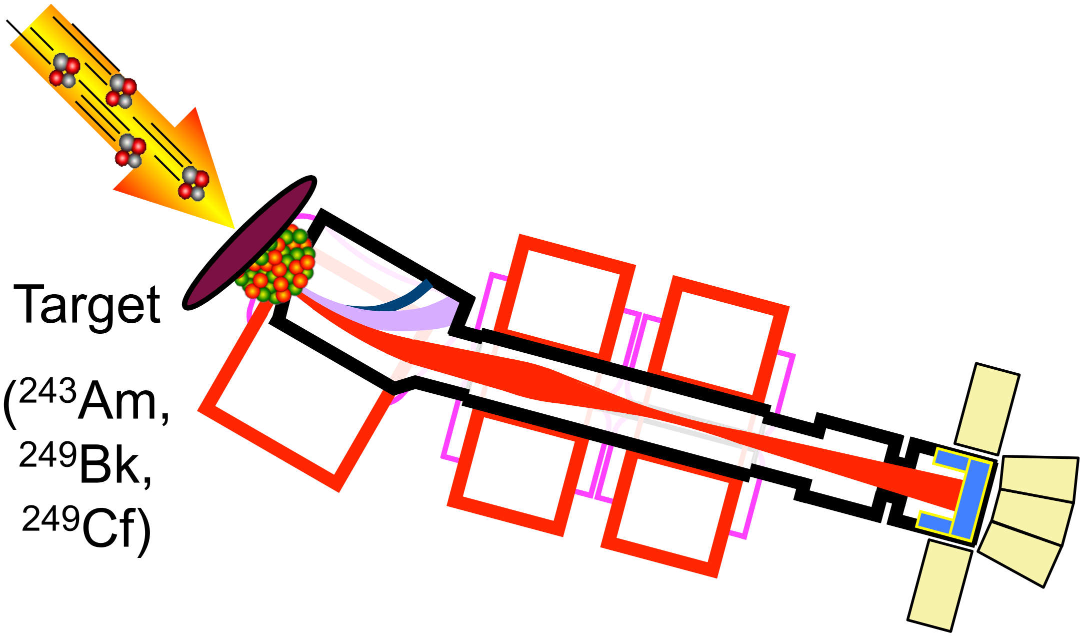


Synthesis, separation and identification of SHE

Beam (^{48}Ca, ^{50}Ti)

Target

(^{243}Am, ^{249}Bk, ^{249}Cf)



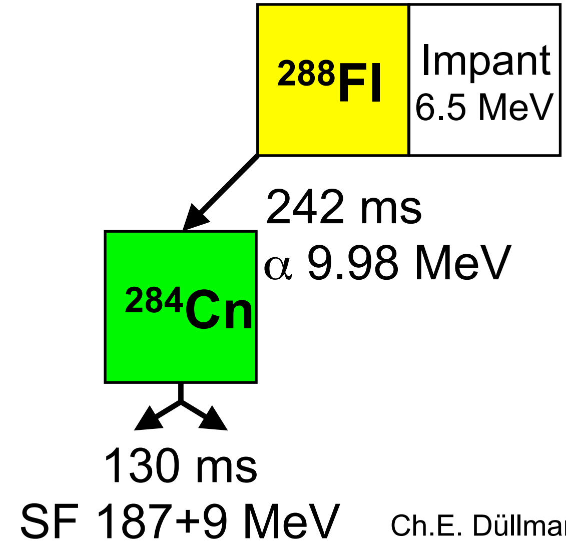
TASCA

TransActinide Separator and Chemistry Apparatus

Particle Detector (α; e^-; SF)

Photon Detector (γ; X)

Detection of decay chain

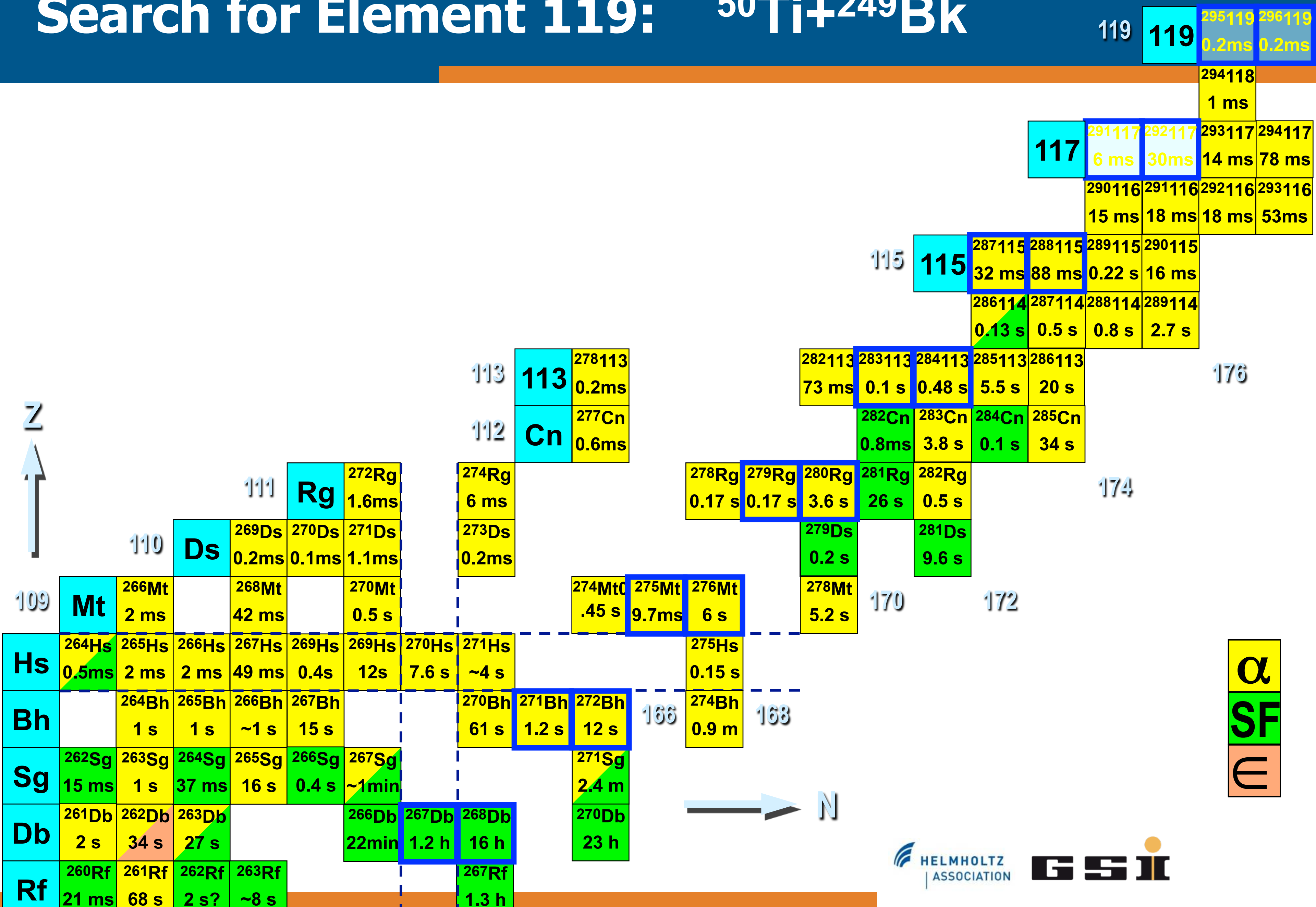


Ch.E. Düllmann et al., PRL 104 (2010) 252701

2012: The *TASCA* Element 119 Collaboration

GSI Darmstadt (D)	D. Ackermann, M. Block, F.P. Heßberger, A. Hübner, E. Jäger, B. Kindler, J. Krier, N. Kurz, B. Lommel, J. Runke, B. Schausten, J. Steiner, A. Yakushev
	EE / Ion source / Accelerator staff
Univ. Mainz (D)	Ch.E. Düllmann, A. Di Nitto, K. Eberhardt, S. Klein, J.V. Kratz, C. Mokry, D. Renisch, P. Thörle-Pospiech, N. Trautmann, N. Wiehl
HIM Mainz (D)	L.-L. Andersson, X. Derkx, J. Even, J. Khuyagbaatar, V. Yakusheva
ORNL / UT Knoxville (USA)	R. Grzywacz, D. Miller, J. Roberto, K. Rykaczewski
Vanderbilt U (USA)	J.H. Hamilton
LBNL / UC Berkeley (USA)	N. Esker, J.M. Gates, K.E. Gregorich, H. Nitsche, G.K. Pang
LLNL (USA)	N. Gharybian, J.M. Gostic, R.A. Henderson, K.J. Moody, D.A. Shaughnessy, E.E. Tereshatov
Lund Univ (S)	C. Fahlander, U. Forsberg, P. Golubev, D. Rudolph
Univ. Liverpool (UK)	D.M. Cox, R.-D. Herzberg, A. Mistry
SINP Kolkata (IND)	S. Lahiri, M. Maiti
JAEA Tokai (J)	M. Asai, M. Schädel
Univ. Oslo (N)	J.P. Omtvedt, A. Semchenkov
U Jyväskylä	J. Uusitalo
PSI / Univ. Berne (CH)	A. Türler, P. Steinegger
ITE Warsaw (PL)	M. Wegrzecki
ANU Canberra (AUS)	M. Evers, D. Hinde

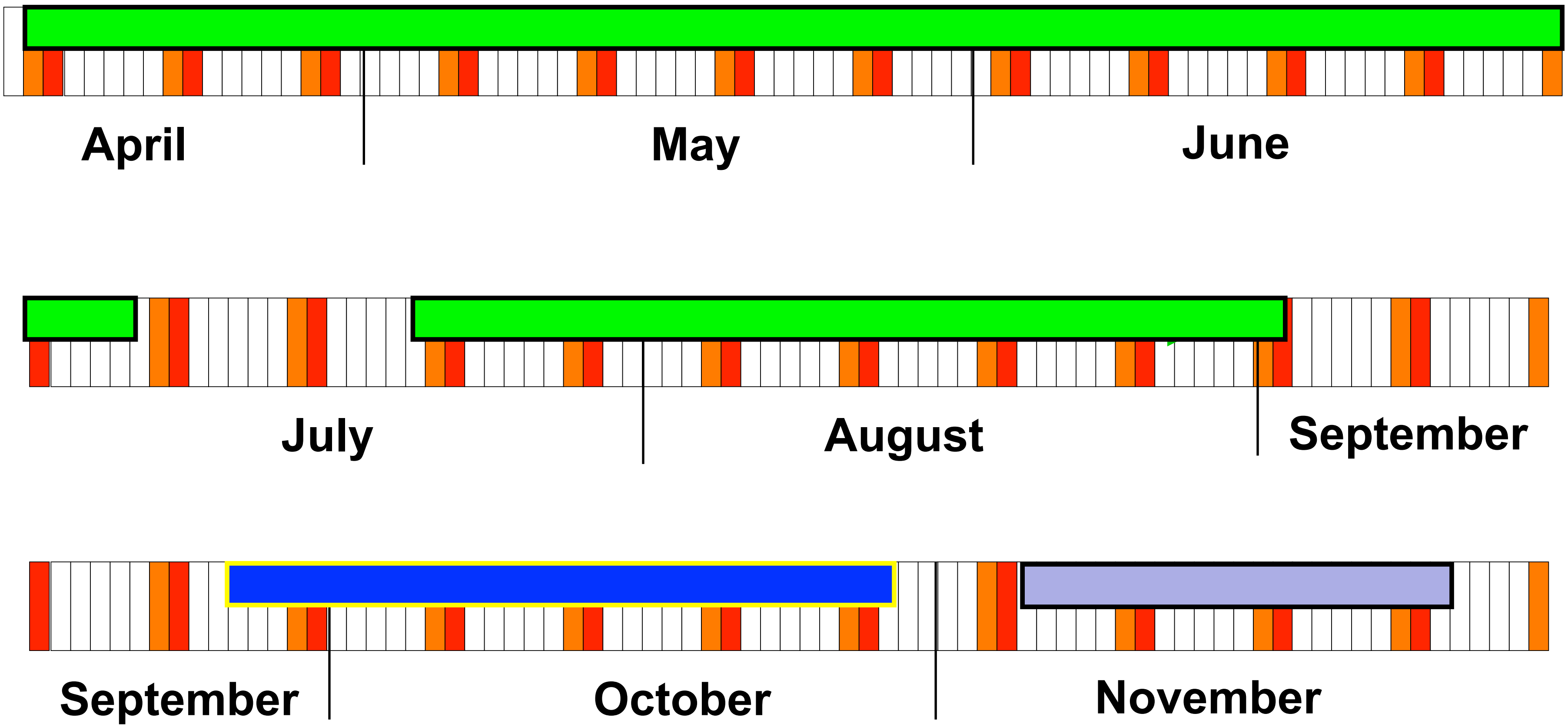
Search for Element 119: $^{50}Ti+^{249}Bk$



Courtesy Ch.E. Düllmann

2012: Element 119 search / Element 117

^{50}Ti beam 750 nA$_p$ and ^{249}Bk targets with initial thickness ≈0.44 mg/cm^2.



^{50}Ti+^{249}Bk⇒Element 119

^{48}Ca+^{249}Bk⇒Element 117

^{48}Ca+^{243}Am⇒Element 115

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Courtesy Ch.E. Düllmann

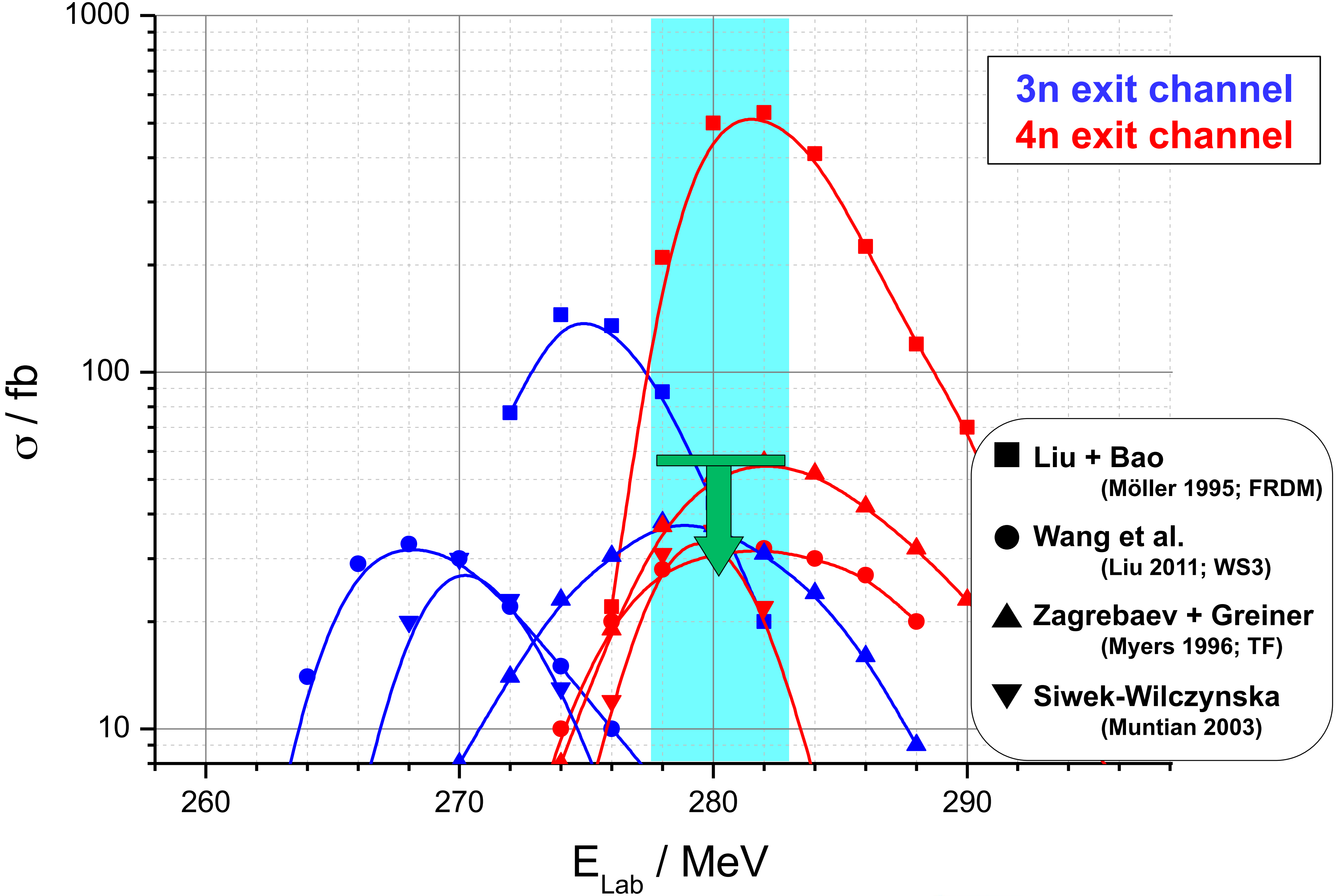
2012: Search for element 119

$^{50}Ti + ^{249}Bk \Rightarrow$ Element 119

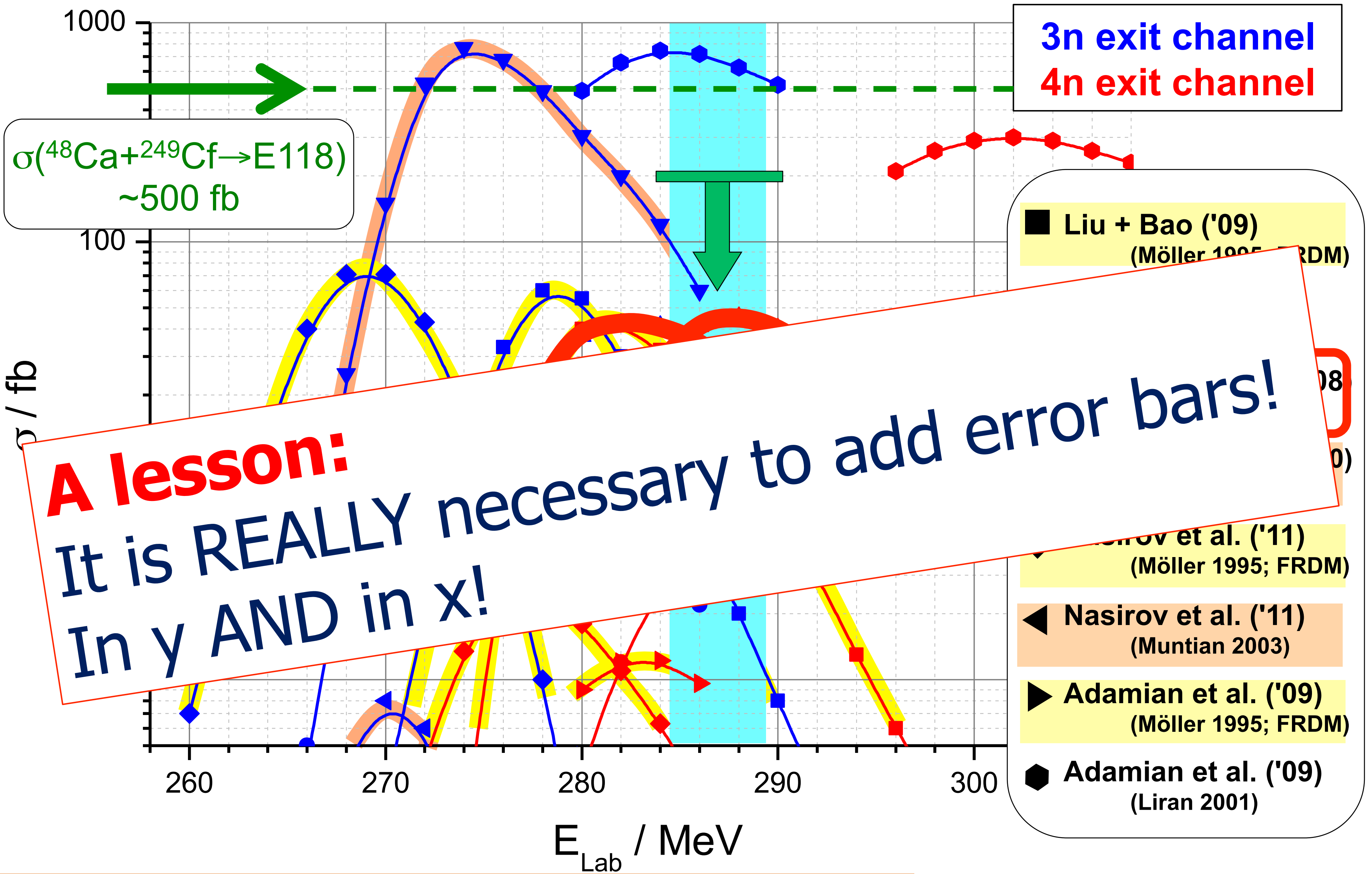
Status of element 119 search:

- beam dose: ≈$3.6 \cdot 10^{19}$ particles
- ≈40 TB of data (analysis is ongoing)
- Sensitivity ≈70 fb for one event (preliminary)
- Current status of data analysis yields no evidence for detection of element 119

$^{50}Ti+^{249}Bk$ Excitation Function



$^{50}Ti+^{249}Cf$ Excitation Function



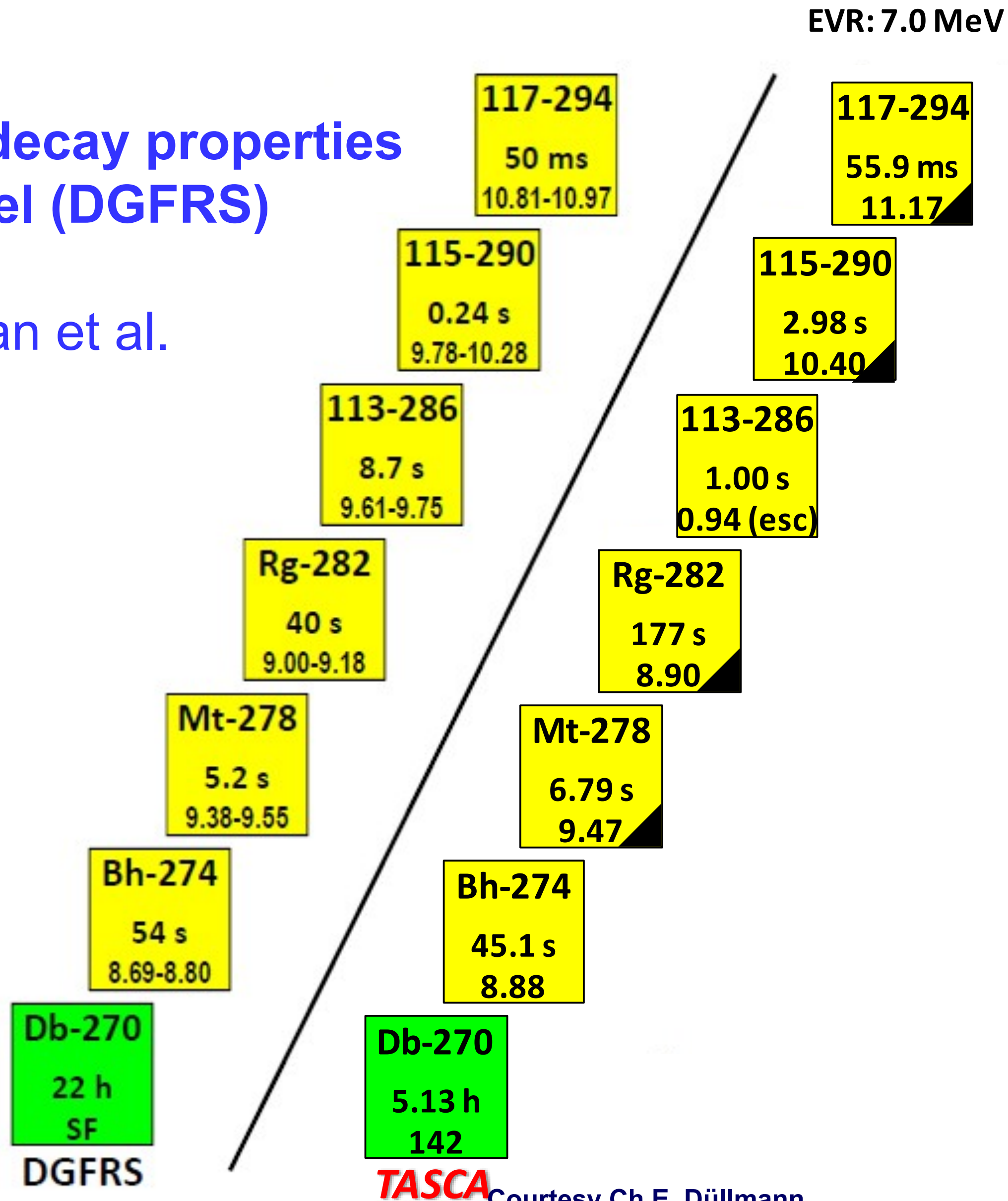
A lesson:
It is REALLY necessary to add error bars!
In y AND in x!

Courtesy Ch.E. Düllmann

First element 117 decay chain from *TASCA*

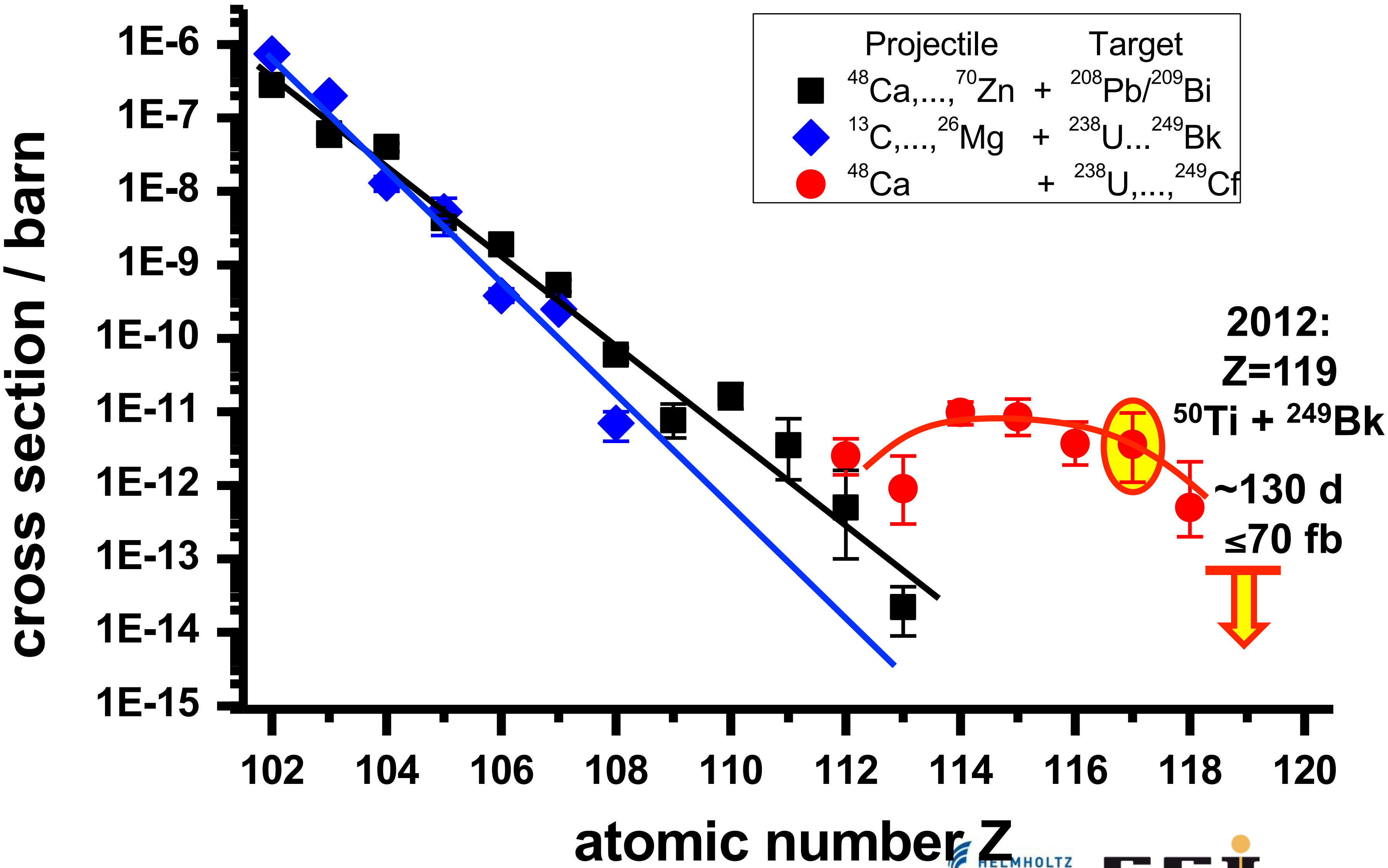
Average decay properties
3n channel (DGFRS)

Oganessian et al.
PRL 2012



Courtesy Ch.E. Düllmann

Cross Sections for SHE Synthesis



The SHIPTRAP collaboration

GSI

HELMHOLTZ
Institut Mainz

LUND UNIVERSITY

LMU

Max-Planck-Institut
für Kernphysik

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

ugr Universidad de Granada

JG|U
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

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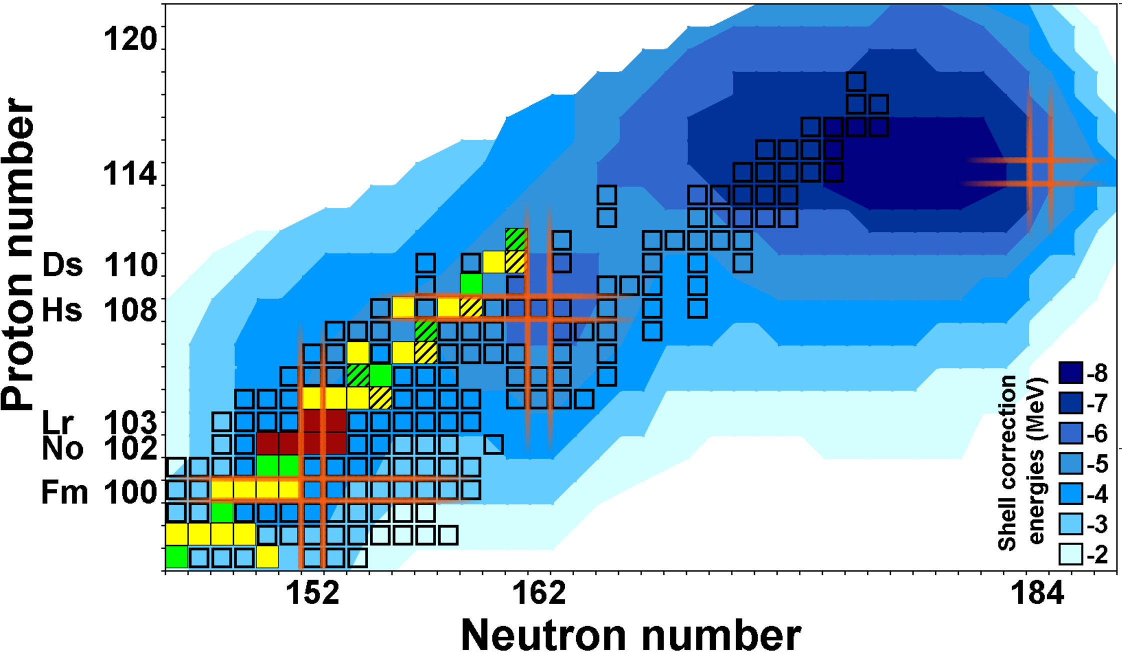
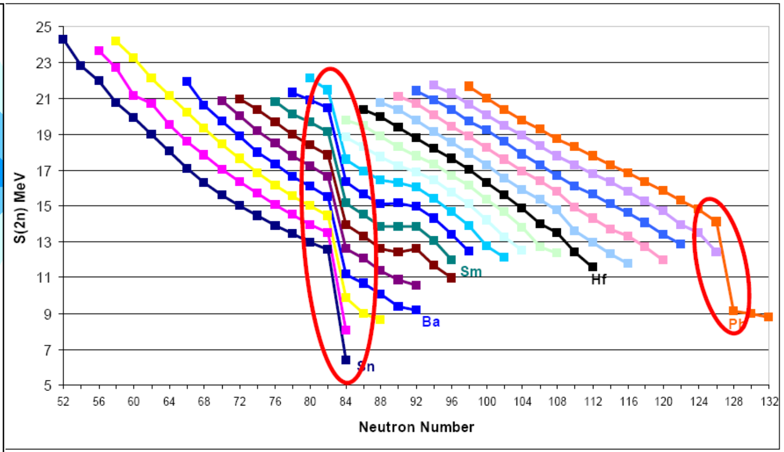
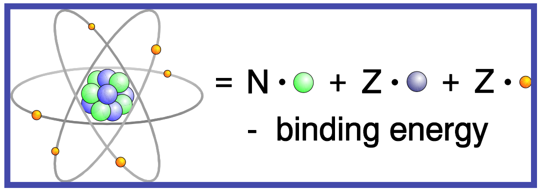
ASSOCIATION

GSI

Importance of Masses for Z > 100







- masses provide absolute nuclear binding energies and allow studies of the shell structure evolution
- high-precision mass measurements provide anchor points to fix decay chains
- benchmark nuclear models

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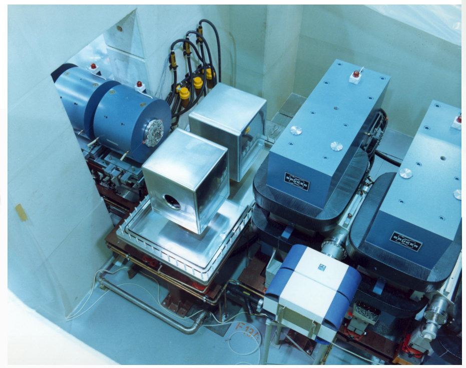
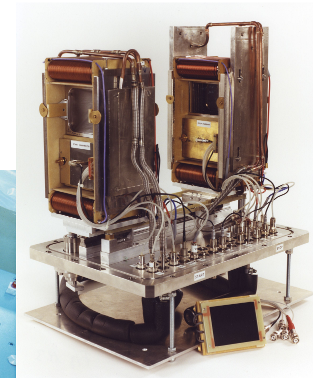
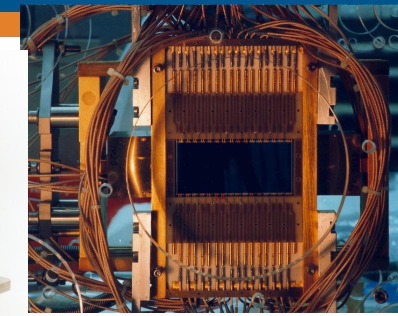
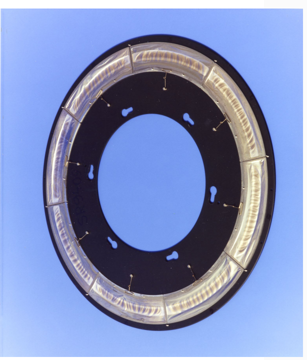
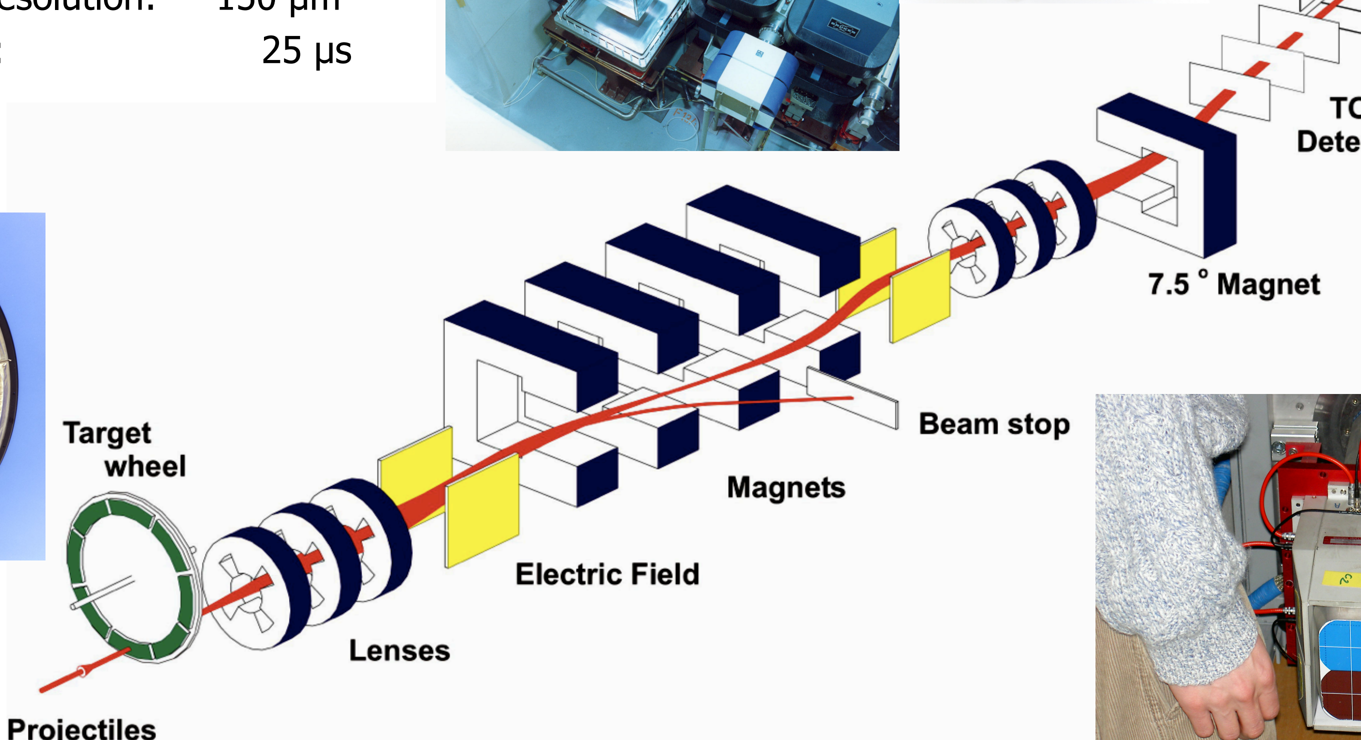
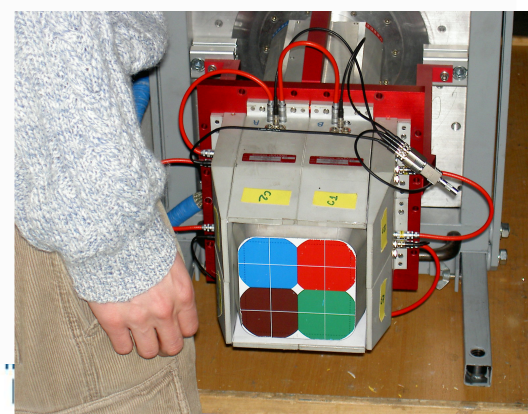
Velocity separator SHIP

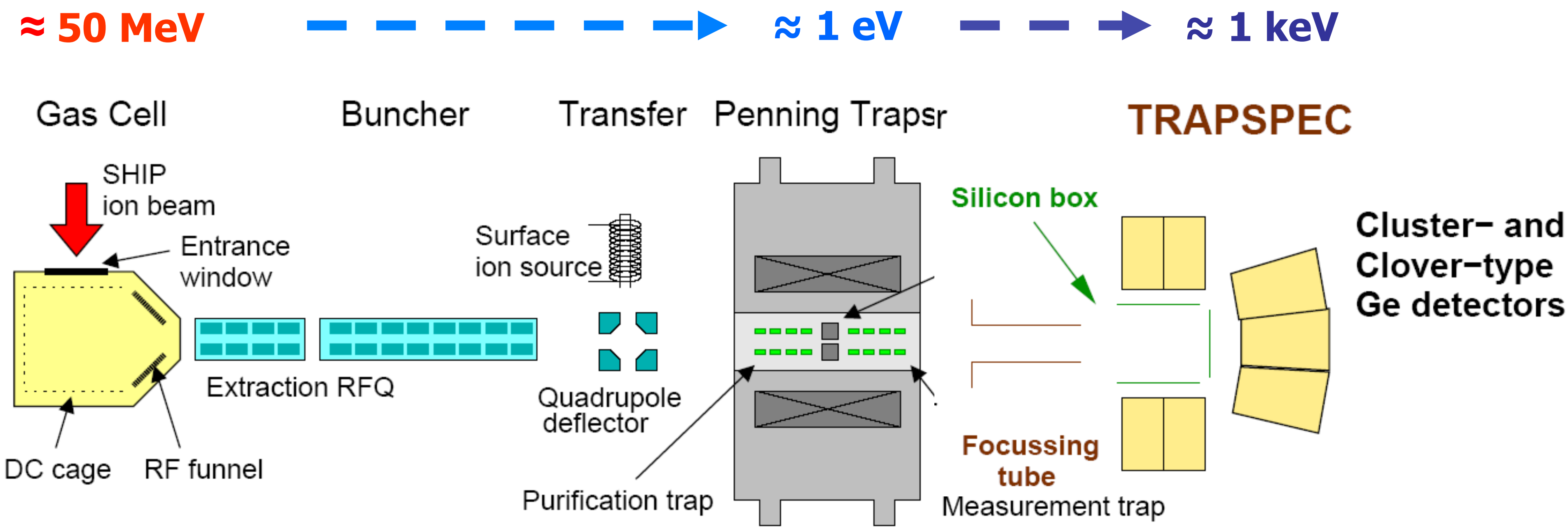
SHIP

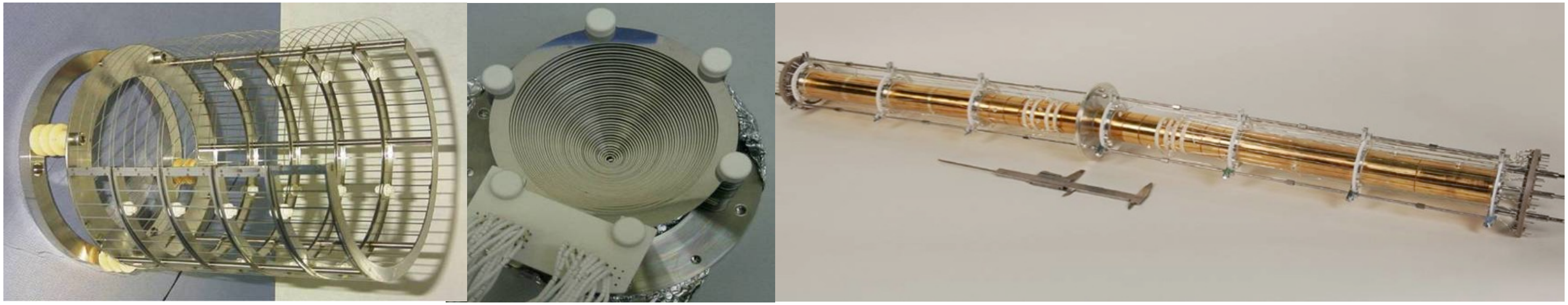
Separation time:	1 – 2 µs
Transmission:	20 – 50 %
Background:	10 – 50 Hz
Det. E. resolution:	18 – 25 keV
Det. Pos. resolution:	150 µm
Dead time:	25 µs



SHIPTRAP Setup





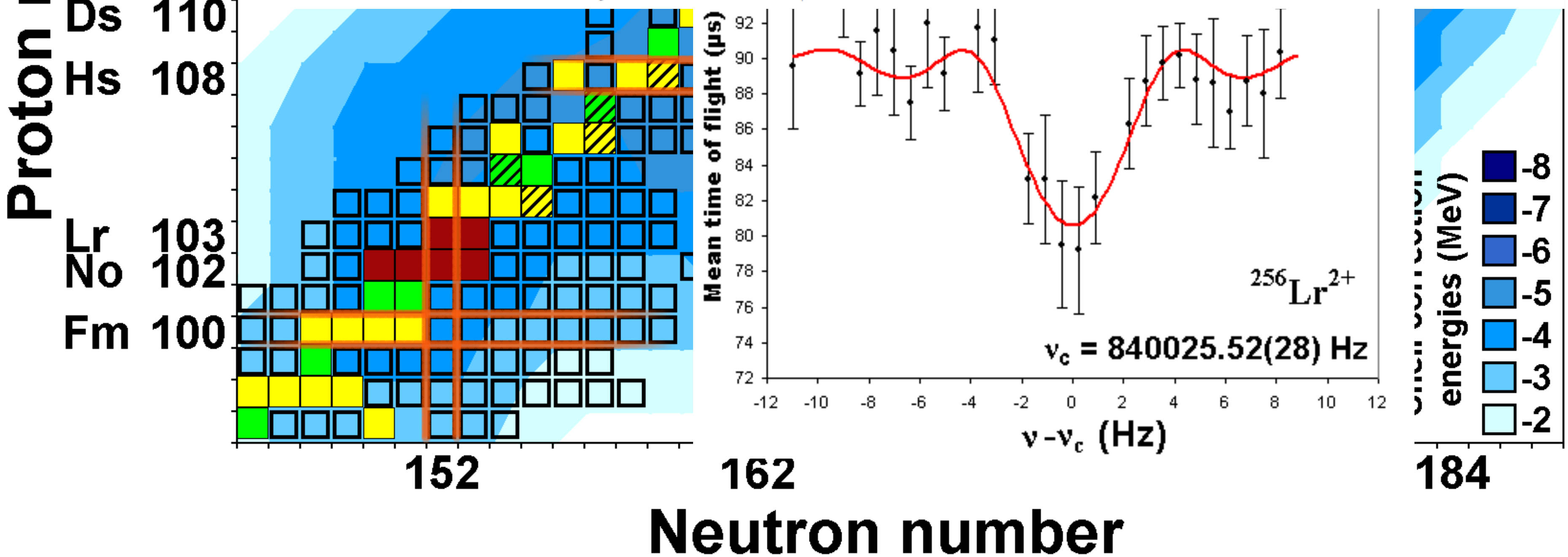
Direct

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

LETTERS

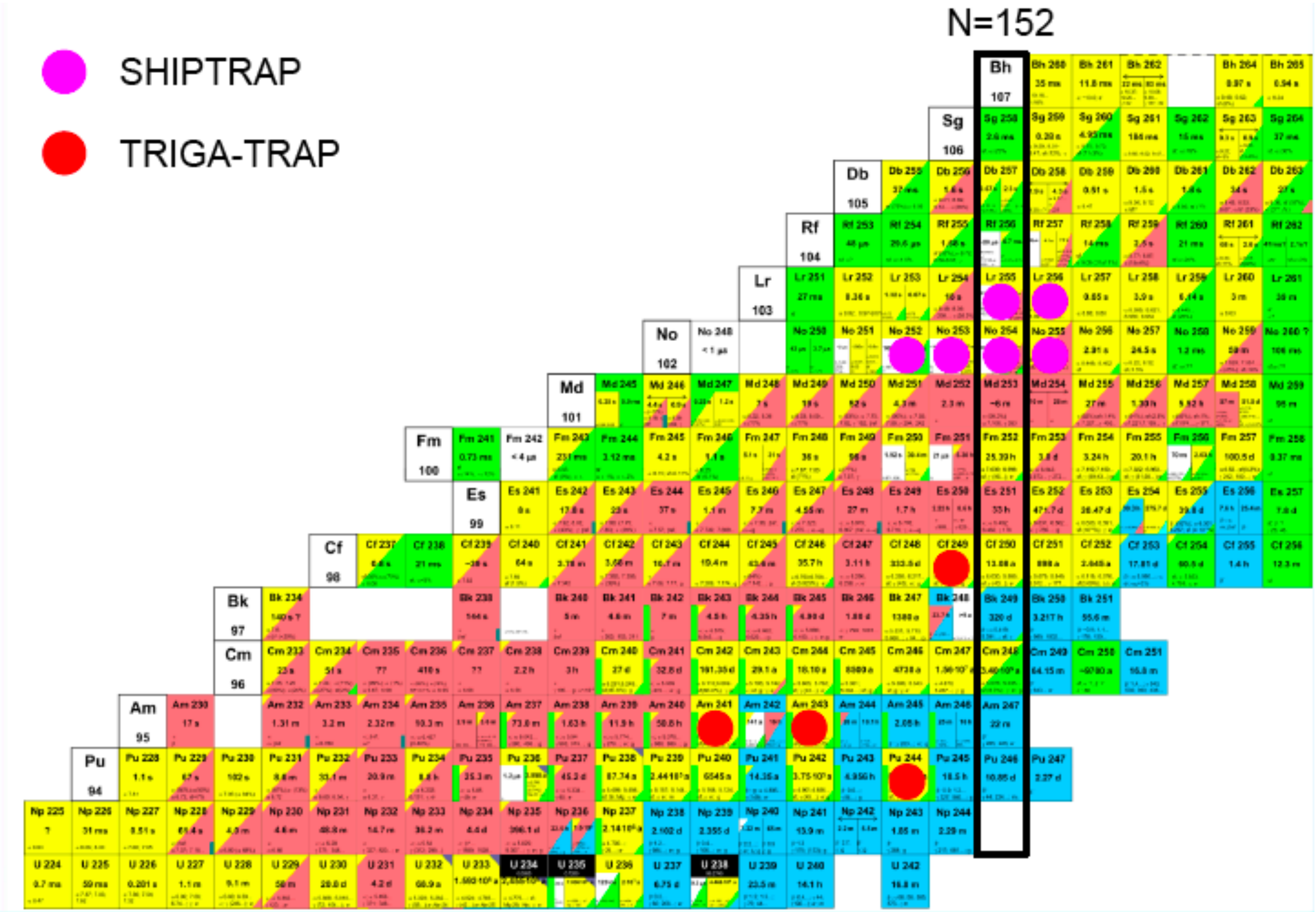
Direct mass measurements above uranium bridge the gap to the island of stability

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]†

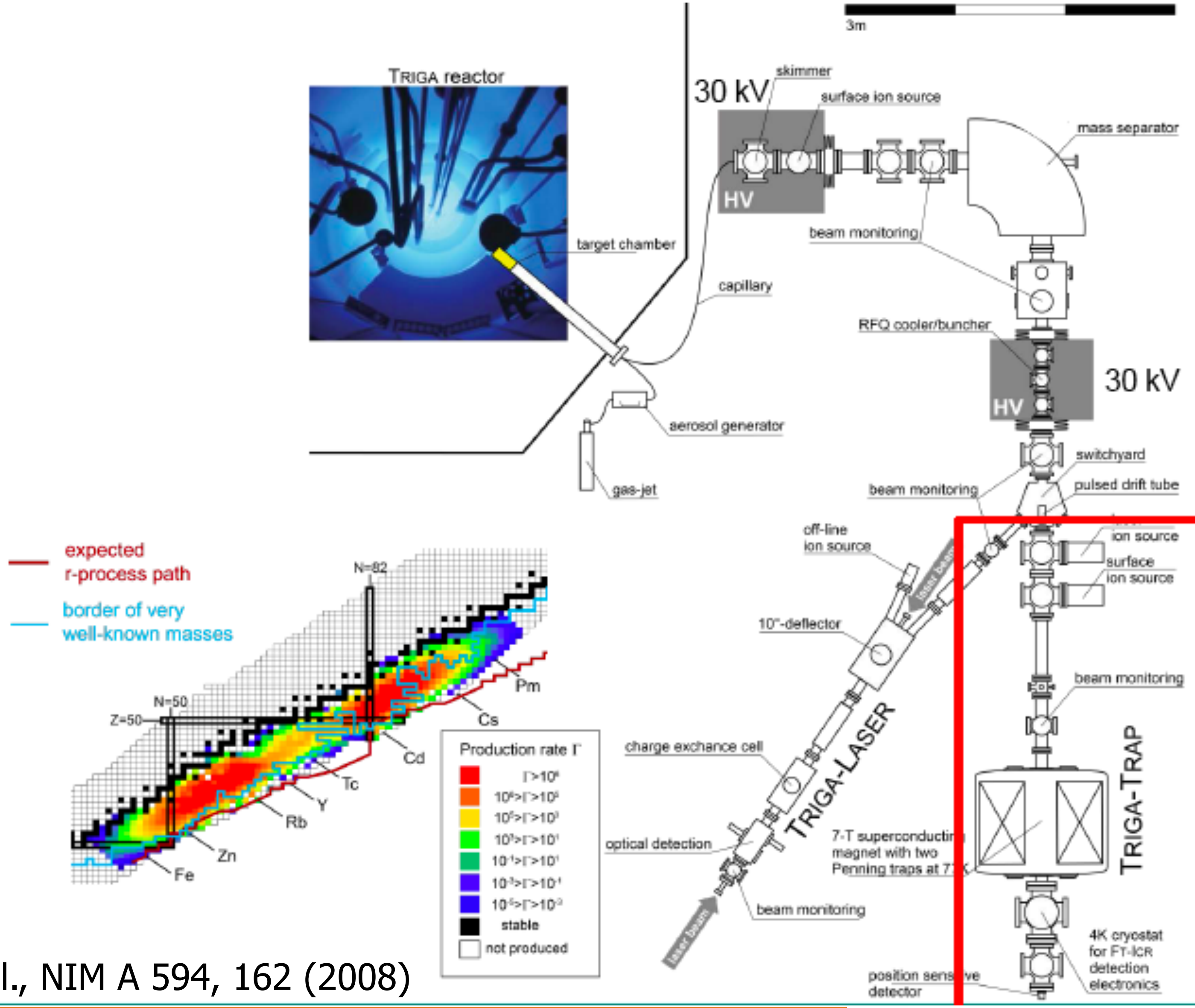


M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

Probing the Strength of Shell Effects @ *N* =152

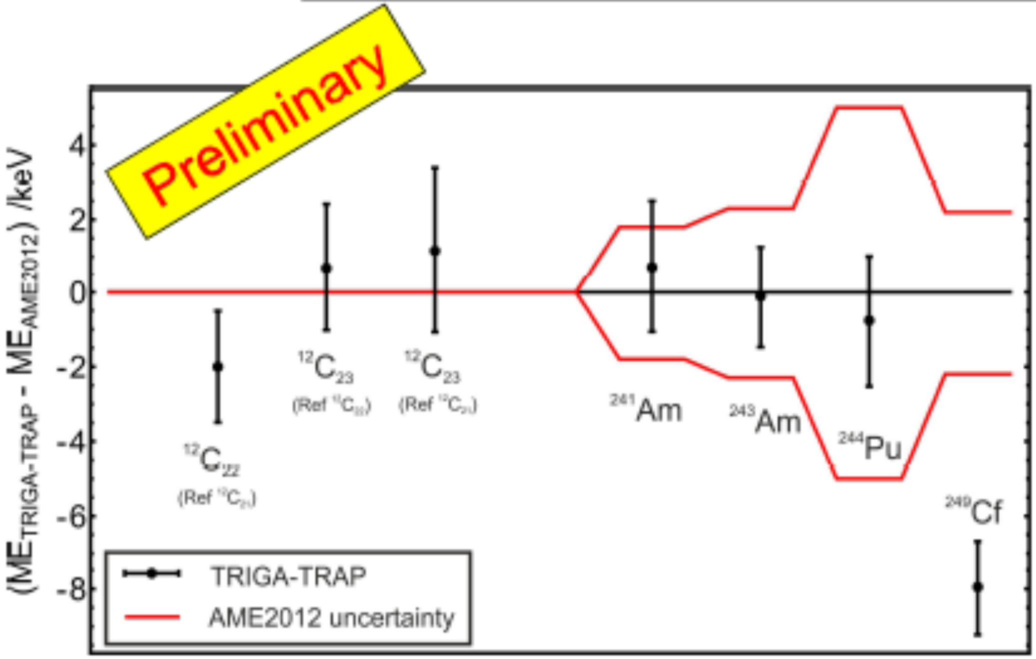


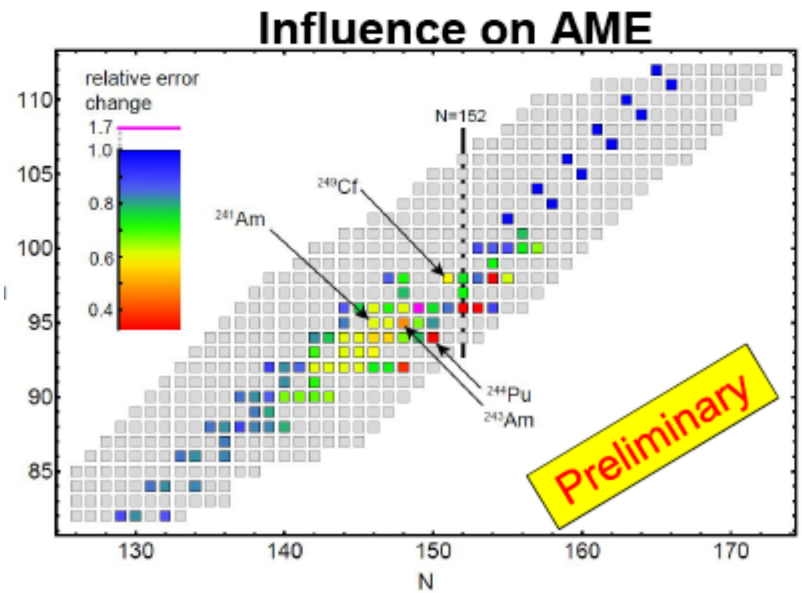
TRIGA-SPEC Setup in Mainz



J. Ketelaer et al., NIM A 594, 162 (2008)

Probing the Evolution of Shell Effects @ *N* =152





Accurate mass measurements with keV precision on long-lived actinides can be performed to provide anchor points and cross check masses obtaiend by other techniques

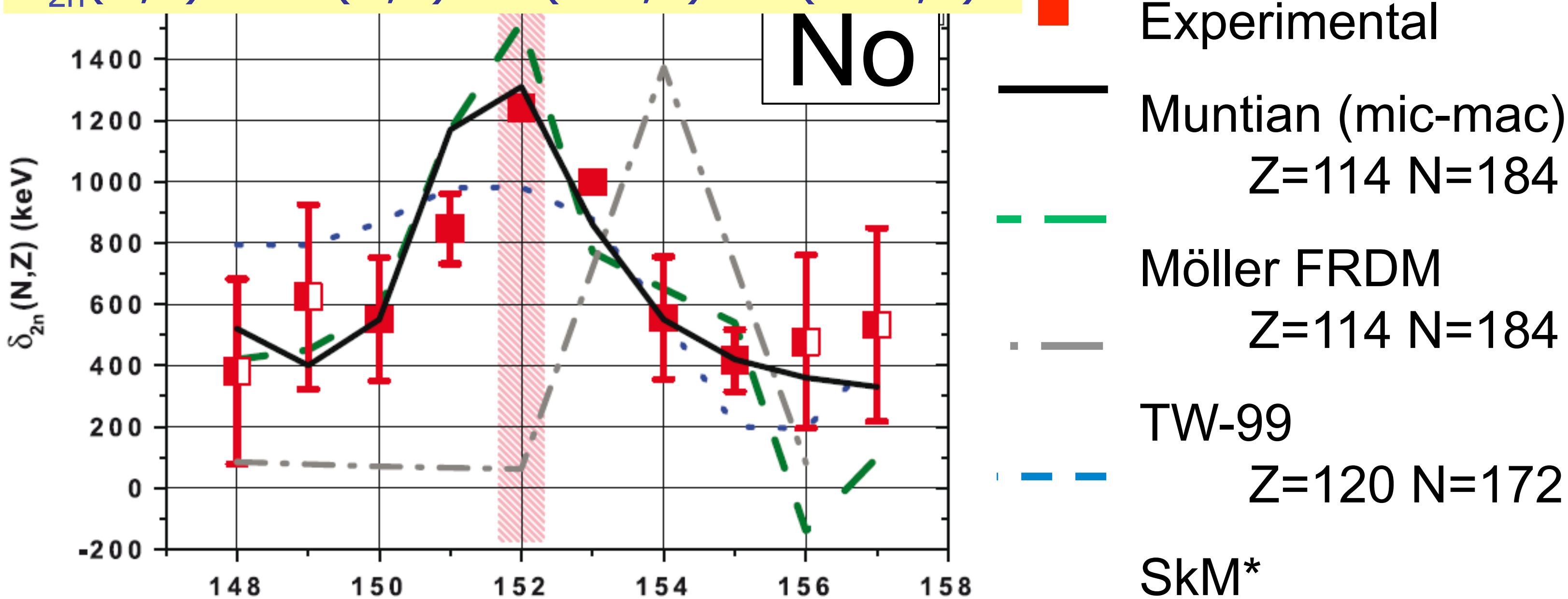
PhD M.Eibach

SHIPTRAP Results on Nuclear Structure

Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

E. Minaya Ramirez,[1,2] D. Ackermann,[2] K. Blaum,[3,4] M. Block,[2*] C. Droese,[5] Ch. E. Düllmann,[6,2,1] M. Dworschak,[2] M. Eibach,[4,6] S. Eliseev,[3] E. Haettner,[2,7] F. Herfurth,[2] F. P. Heßberger,[2,1] S. Hofmann,[2] J. Ketelaer,[3] G. Marx,[5] M. Mazzocco,[8] D. Nesterenko,[9] Yu. N. Novikov,[9] W. R. Plaß,[2,7] D. Rodríguez,[10] C. Scheidenberger,[2,7] L. Schweikhard,[5] P. G. Thirolf,[11] C. Weber[11]

$$\delta_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z)$$



Science **337** (2012) 1207

SHIP – SHE Spectroscopy Collaboration:

GSI, Darmstadt
D.Ackermann, M.B., S.Heinz, F.P.Hessberger, S.Hofmann, B.Kindler, I.Kojouharov, J.Khuyagbaatar, B.Lommel

Helmholtz Institut Mainz
L.-L.Andersson, E. Minaya, M. Laatiaoui

Comenius University Bratislava, Slovakia
S. Antalic, Z.Kalininova

Ernst-Moritz-Arndt Universität Greifswald, Germany
C. Droese

University Jyväskylä, Finland
M.Leino, J.Uusitalo

JAEA Tokai, Japan
K. Nishio

FLNR – JINR Dubna, Russia
A.G.Popeko, A.Yeremin

Theory Support: A. Sobiczewski (NCNR Warsaw, Poland)
E. Litvinova (EMMI Darmstadt, Germany; MSU East Lansing, USA)
D. Vretenar, Lu Bingnan (Univ. Zagreb, Croatia)

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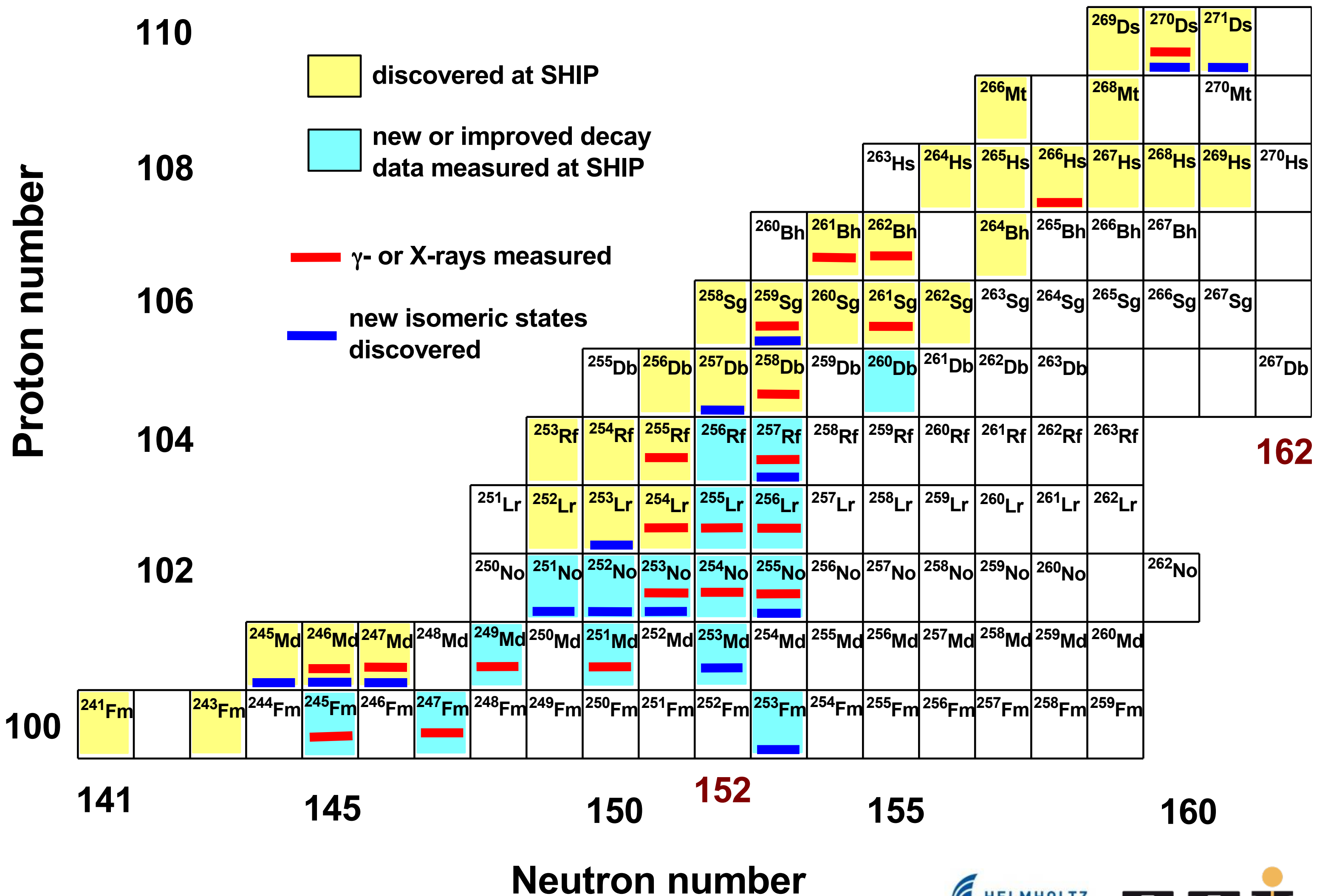
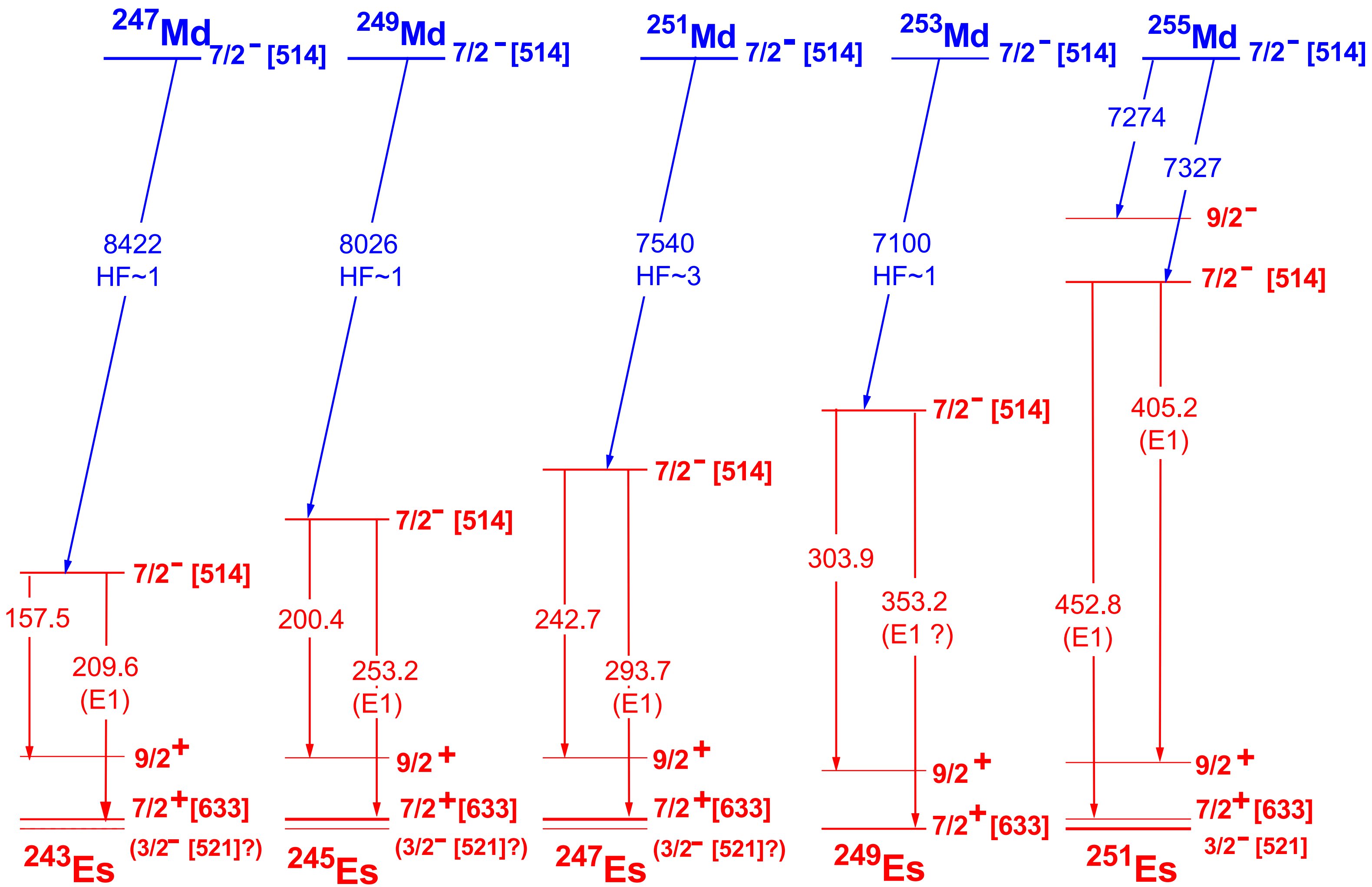
Playground for Nuclear Structure Investigations in the Transfermium Region



Decay schemes of odd-mass Md-isotopes
(simplified)



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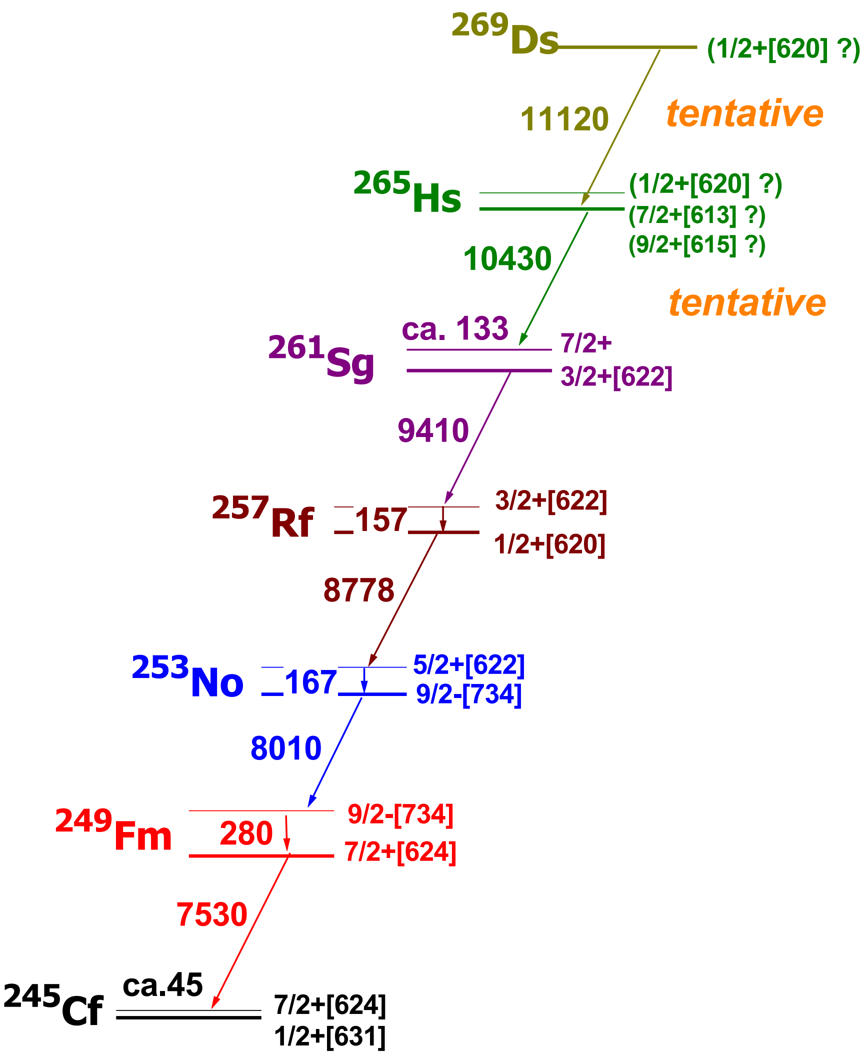
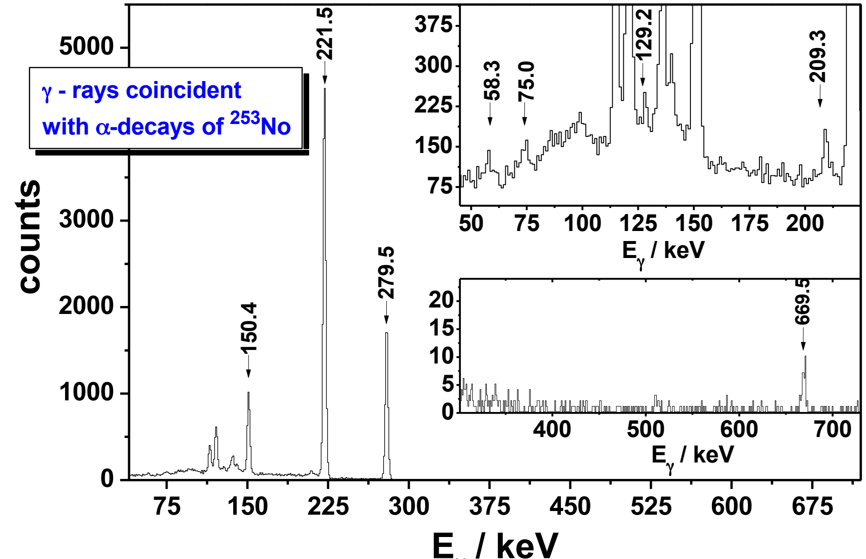
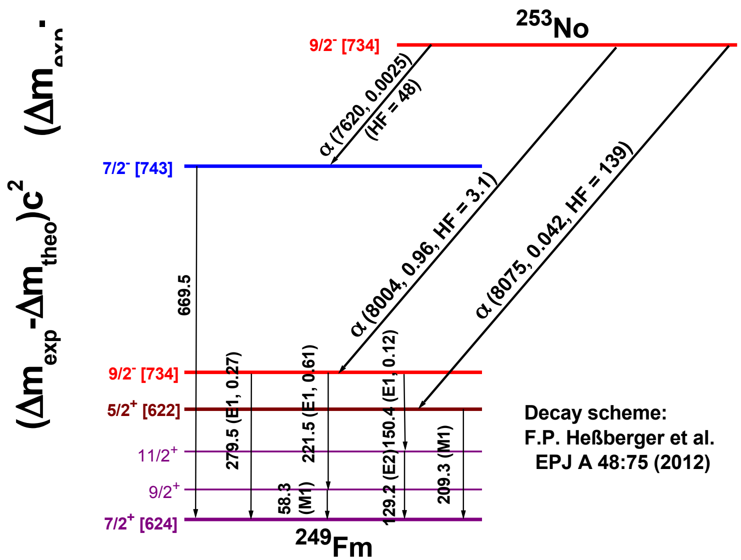
Courtesy F.P. Hessberger

Masses of odd-A N-Z = 51 Nuclei
Symbiosis of Mass Measurements and Spectroscopy

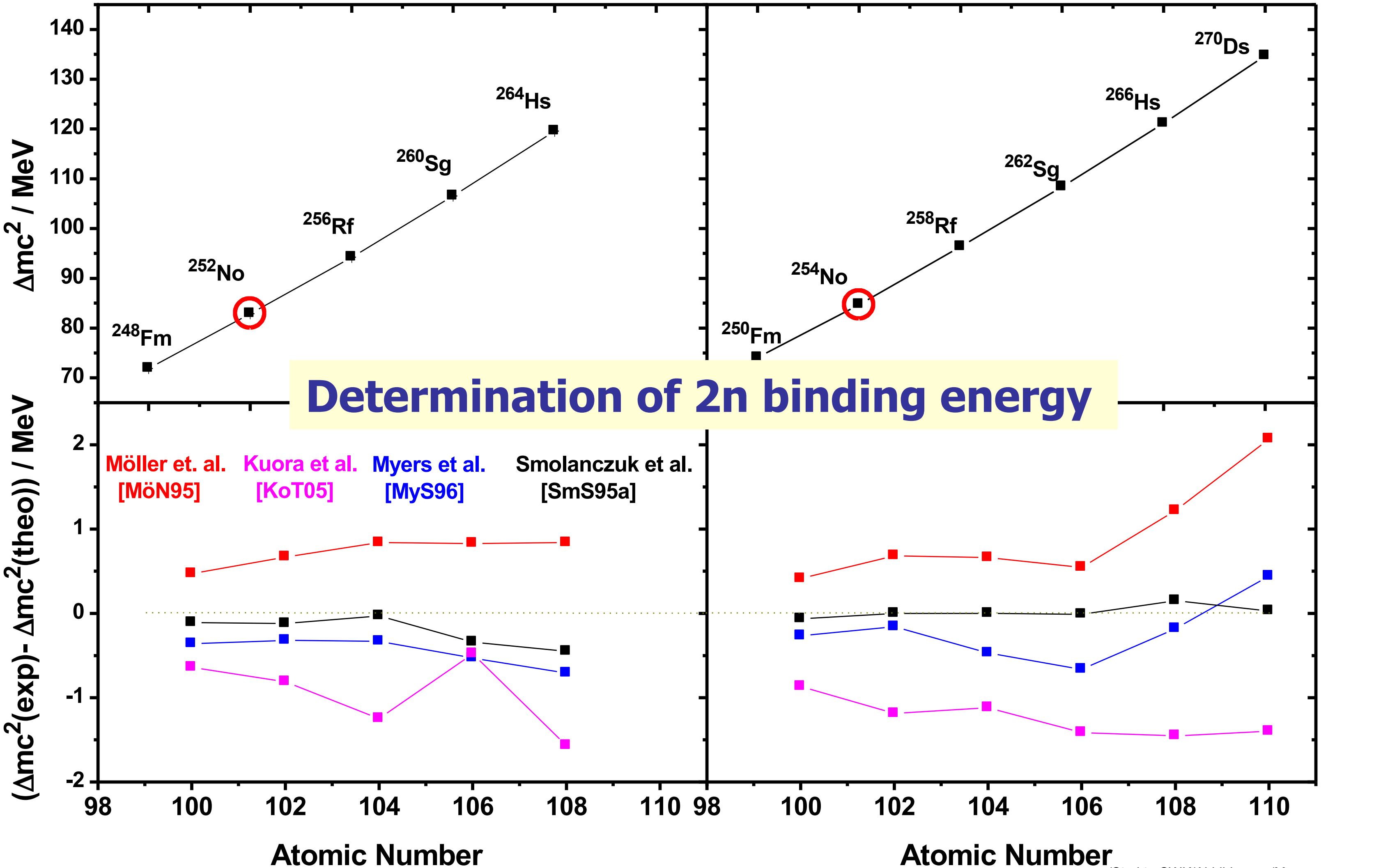






Decay scheme:
F.P. Heßberger et al.
EPJ A 48:75 (2012)

Masses of even-even N-Z = 48 and N -Z = 50 Nuclei



/StrukturSWK/Abbildungen/Massen,
F.P. Heßberger, 3.9.2013

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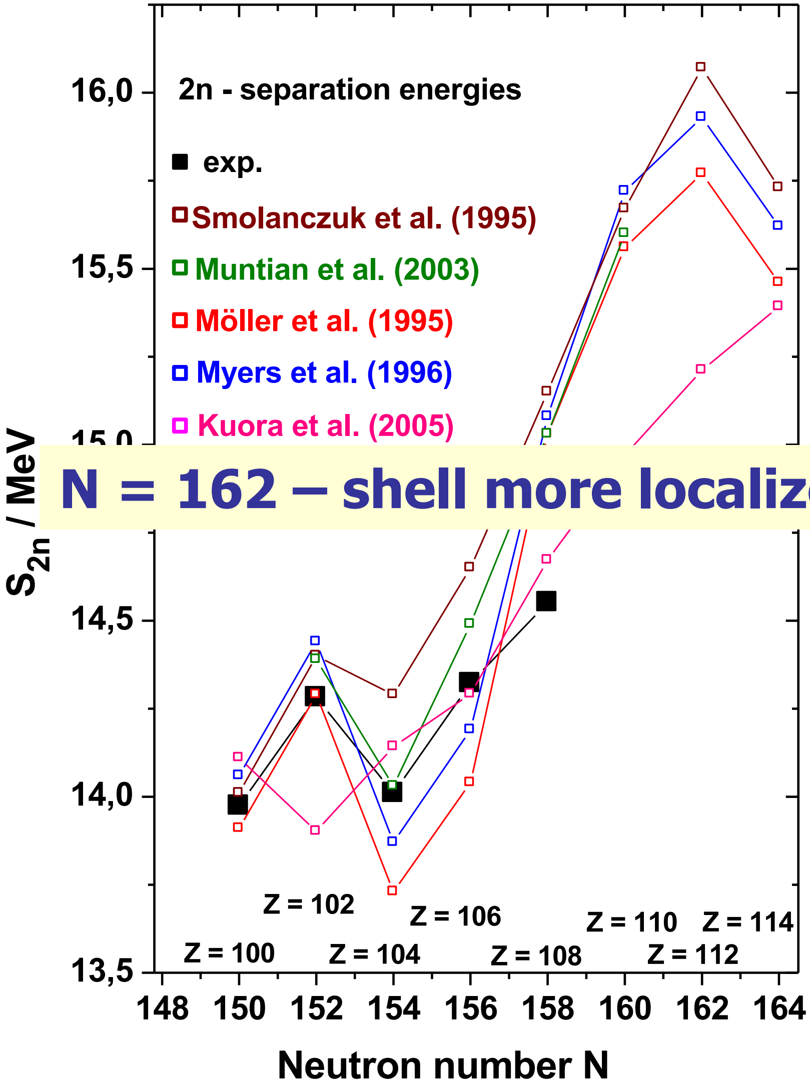
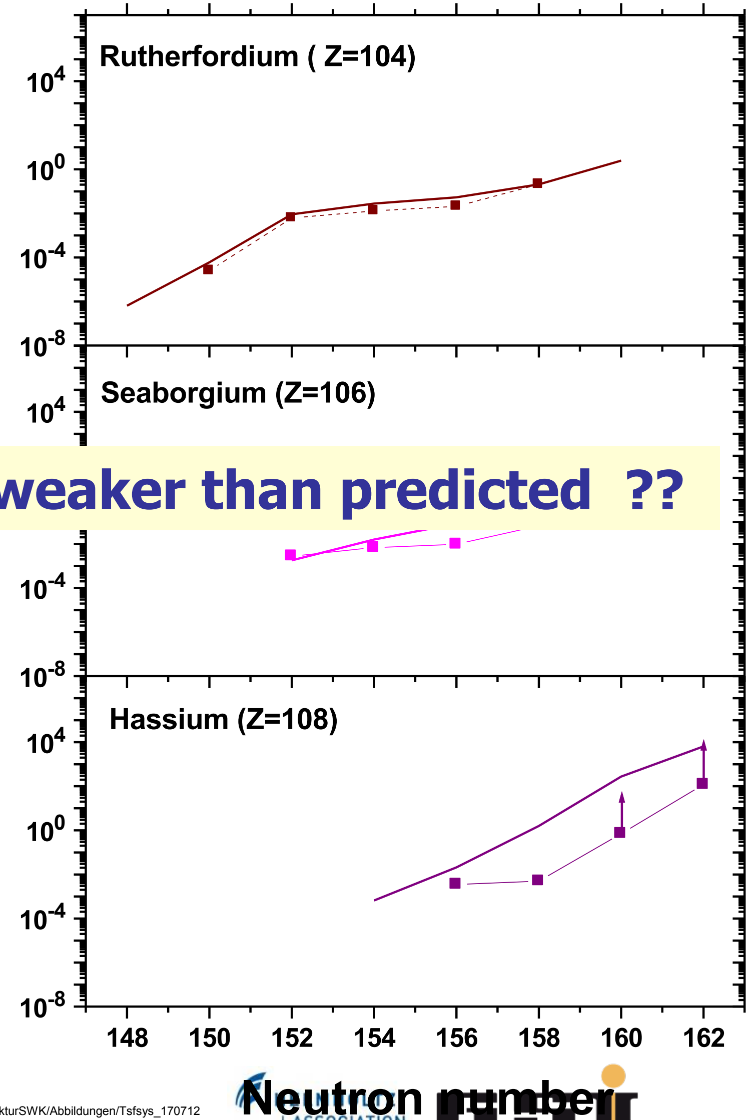
Development of 2n-Separation energies towards deformed neutron shell at N = 162





N = 162 – shell more localized or weaker than predicted ??

/StrukturSWK/Abbildungen/Massen,
F.P. Heßberger, 10.4.2013

/StrukturSWK/Abbildungen/Tsfsys_170712
Status: 6. 3. 2012

Courtesy F.P. Hessberger

The TASISpec / *TASCA* E115 Collaboration

PHYSICAL REVIEW LETTERS 111, 112502 (2013)

Spectroscopy of Element 115 Decay Chains

D. Rudolph,[1,*] U. Forsberg,[1] P. Golubev,[1] L. G. Sarmiento,[1] A. Yakushev,[2] L.-L. Andersson,[3] A. Di Nitto,[4] Ch. E. Düllmann,[2,3,4] J. M. Gates,[5] K. E. Gregorich,[5] C. J. Gross,[6] F. P. Heßberger,[2,3] R.-D. Herzberg,[7] J. Khuyagbaatar,[3] J. V. Kratz,[4] K. Rykaczewski,[6] M. Schädel,[2,8] S. Åberg,[1] D. Ackermann,[2] M. Block,[2] H. Brand,[2] B. G. Carlsson,[1] D. Cox,[7] X. Derkx,[3,4] K. Eberhardt,[3,4] J. Even,[3] C. Fahlander,[1] J. Gerl,[2] E. Jäger,[2] B. Kindler,[2] J. Krier,[2] I. Kojouharov,[2] N. Kurz,[2] B. Lommel,[2] A. Mistry,[7] C. Mokry,[3,4] H. Nitsche,[5] J. P. Omtvedt,[9] P. Papadakis,[7] I. Ragnarsson,[1] J. Runke,[2] H. Schaffner,[2] B. Schausten,[2] P. Thörle-Pospiech,[3,4] T. Torres,[2] T. Traut,[4] N. Trautmann,[4] A. Türler,[10] A. Ward,[7] D. E. Ward,[1] and N. Wiehl[3,4]

[1]*Lund University, 22100 Lund, Sweden*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[3]*Helmholtz Institute Mainz, 55099 Mainz, Germany*
[4]*Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[5]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[6]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[7]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[8]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[9]*University of Oslo, 0315 Oslo, Norway*
[10]*Paul Scherrer Institute and University of Bern, 5232 Villigen, Switzerland*

(Received 11 June 2013)

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GSI

HIM

JGU

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

OAK RIDGE National Laboratory

JAEA

PAUL SCHERRER INSTITUT PSI

UNIVERSITY OF LIVERPOOL

UiO: University of Oslo

Special thanks to …

UNILAC

KUNGL. FYSIOGRAFISKA SÄLLSKAPET I LUND

ENSAR

Spokesman: Dirk Rudolph, Lund

HELMHOLTZ ASSOCIATION

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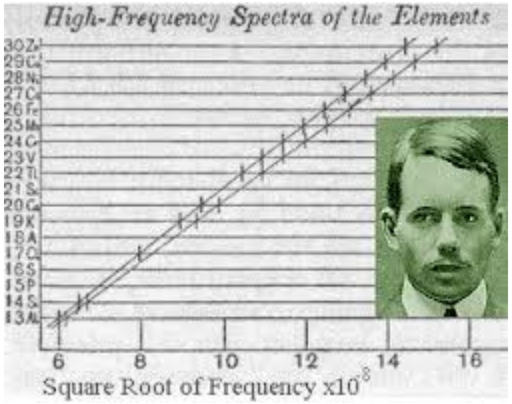
X-ray Fingerprinting of an Element

Moseley's Law, 1913

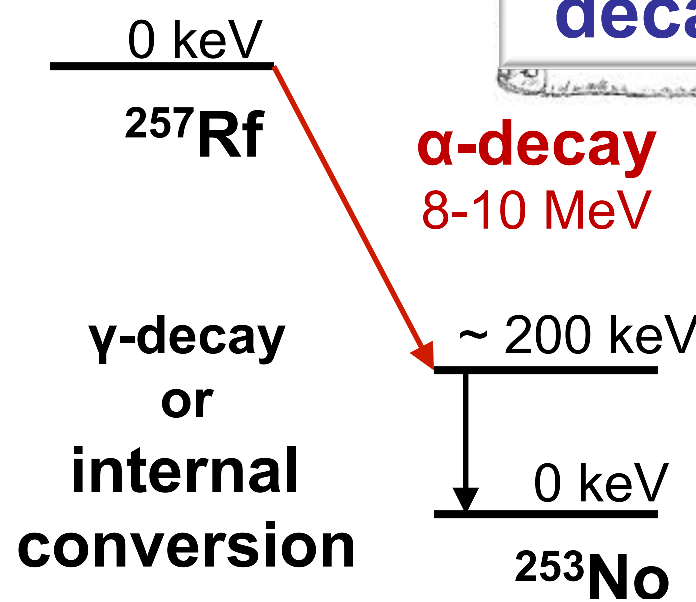


$$E(K_\alpha) \sim f(K_\alpha) \sim (Z\text{-}1)^2$$

H.G.J. Moseley, Phil. Mag. 26, 1024 (1913)

***X*-ray energies predicted down to 0.1 keV precision for superheavy elements (QED!)**

Highest *K*-conversion coefficients!



R. Bemis *et al.*, PRL31, 647 (1973)
(observed 15 α-photon events)

X-ray Fingerprinting of Element 115

- long odd-mass or odd-odd decay chains
- reasonable production cross section

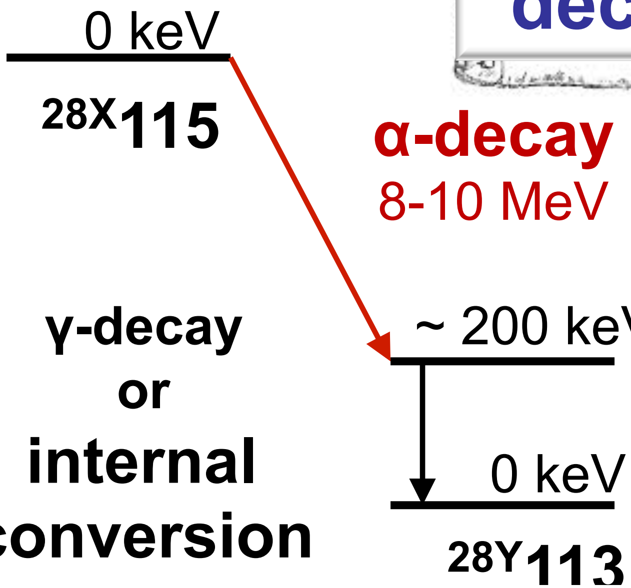
Z **- identification along E115 chains (sequence of 5 α decays)**

2009: 12 weeks of beamtime requested

2010: 8 weeks PAC approved and granted

2012: 3 weeks scheduled

Highest *K*-conversion coefficients!



in the Rutherfordium spirit of

R. Bemis *et al.*, PRL31, 647 (1973)

(observed 15 α-photon events)

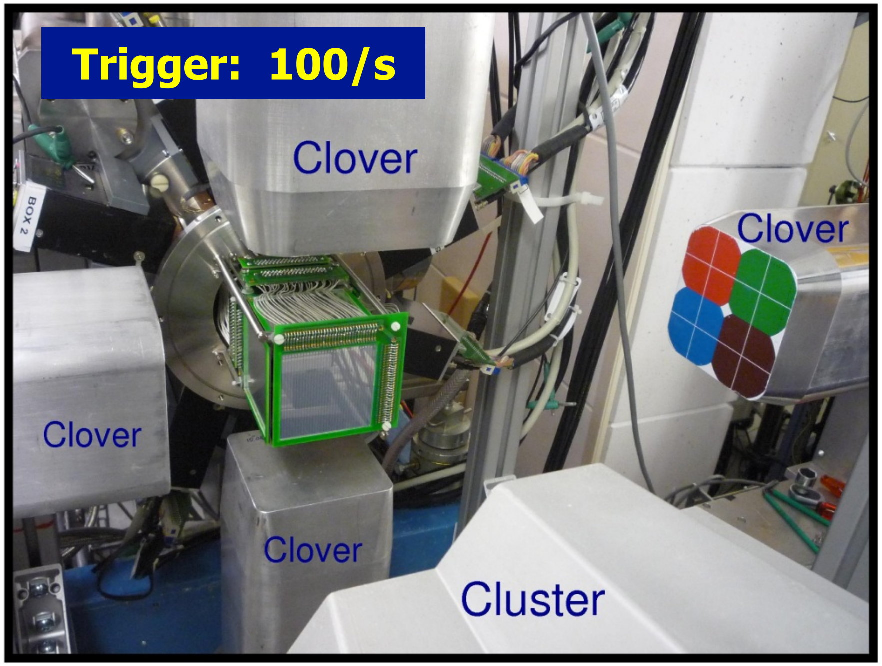
TASiSpec

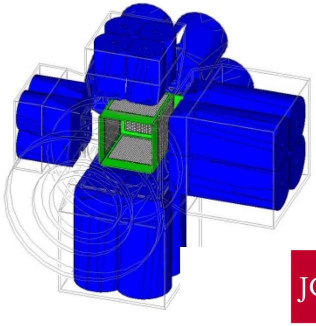
Highly efficient multi–coincidence spectroscopy set–up for TASCA's very compact focal plane image

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

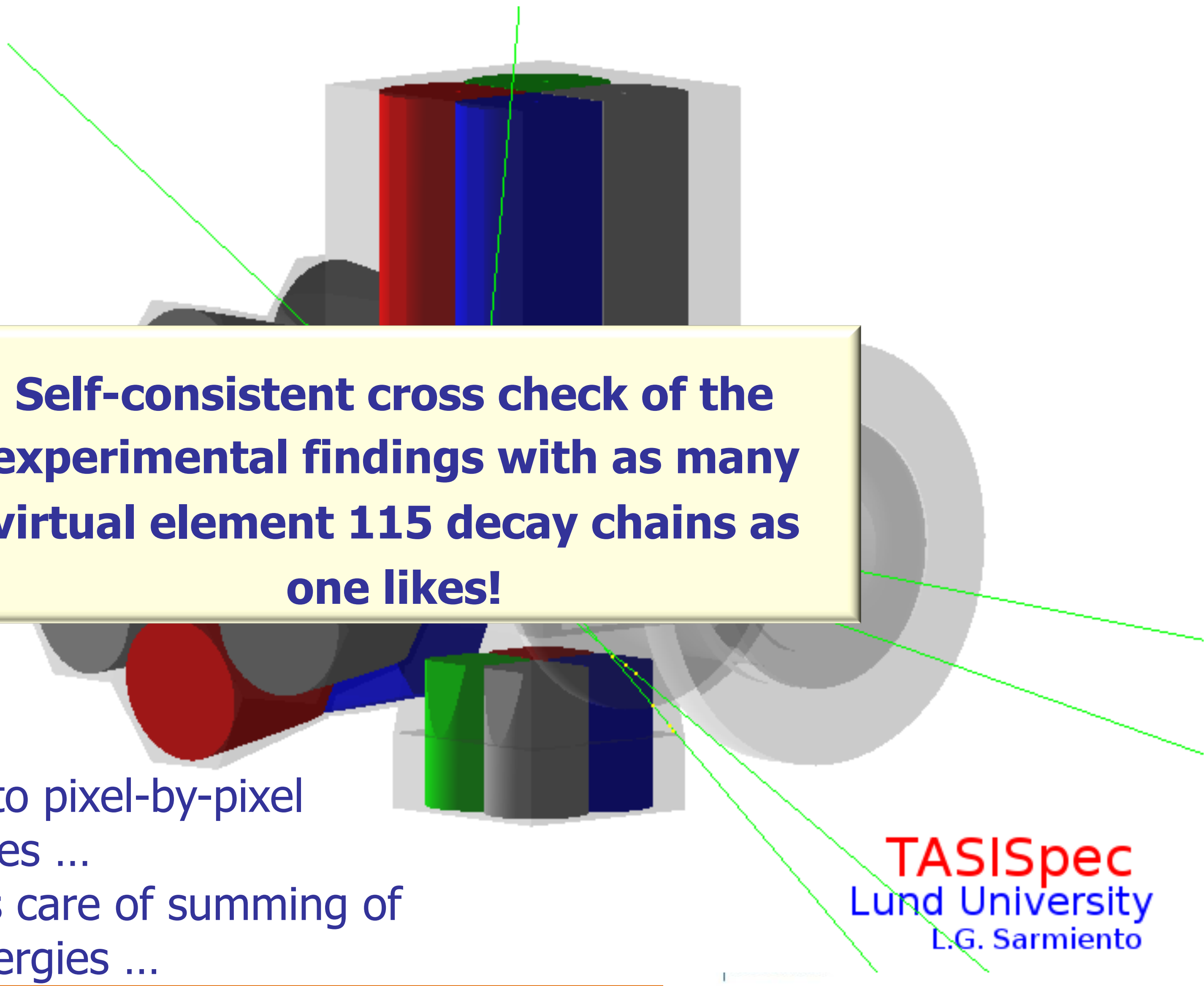




Virtually constructed with GEANT4 simulation package

LUND UNIVERSITY
UNIVERSITY OF LIVERPOOL
HELMHOLTZ | ASSOCIATION
Helmholtz Institute Mainz
GSI
UNIVERSIDAD NACIONAL DE COLOMBIA
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TASISpec – in Virtual GEANT4 Space



Self-consistent cross check of the experimental findings with as many virtual element 115 decay chains as one likes!

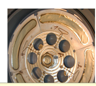
"Input level": down to pixel-by-pixel dead-layer thicknesses …
"Output level": takes care of summing of α, CE, and Auger energies …

Some Experimental Numbers

Date & place: November 2012, 3 weeks, ***TASCA,*** GSI

Beam: ^{48}Ca pulsed (5 ms on, 15 ms off)
time averaged 1 particle µA ($6 \cdot 10^{12}$/s)

Target: ^{243}Am



material from OAK RIDGE National Laboratory production at JG|U

ing

Beam e 0^{18}

TASC

Transm

Trigger

Beam s

30 correlated decay chains of element 115 in 3 weeks of beamtime!

$\sigma_{tot} \sim$ 10 pb

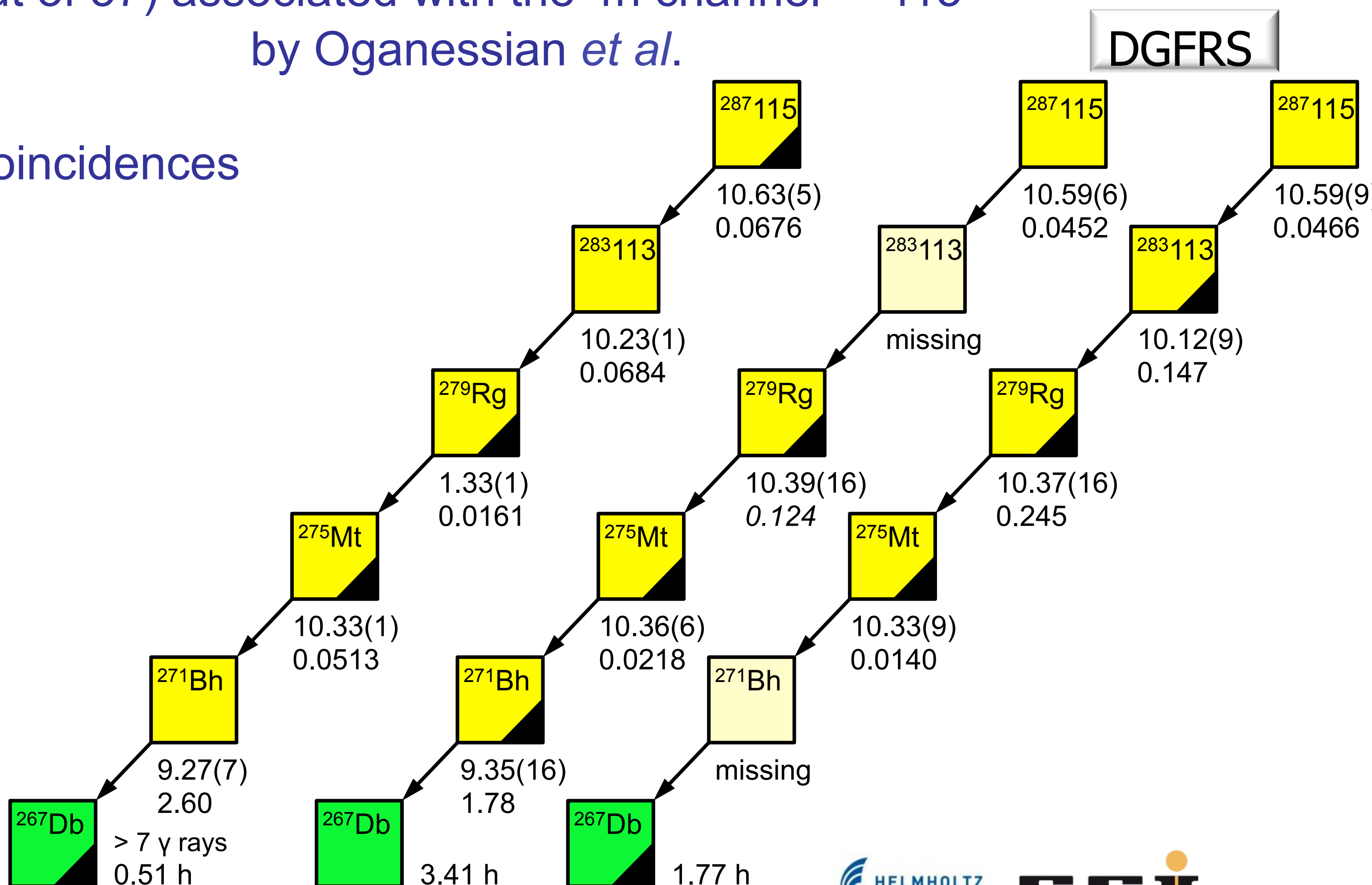
Only 64 beam-off fission events in 3 weeks spread over 1024 DSSSD pixels.

Courtesy D. Rudolph

Results – ^{287}115 (4n-channel)

1 chain (out of 30) of ours is compatible with the
2 chains (out of 37) associated with the 4n channel ^{287}115
by Oganessian *et al*.

no α-photon coincidences



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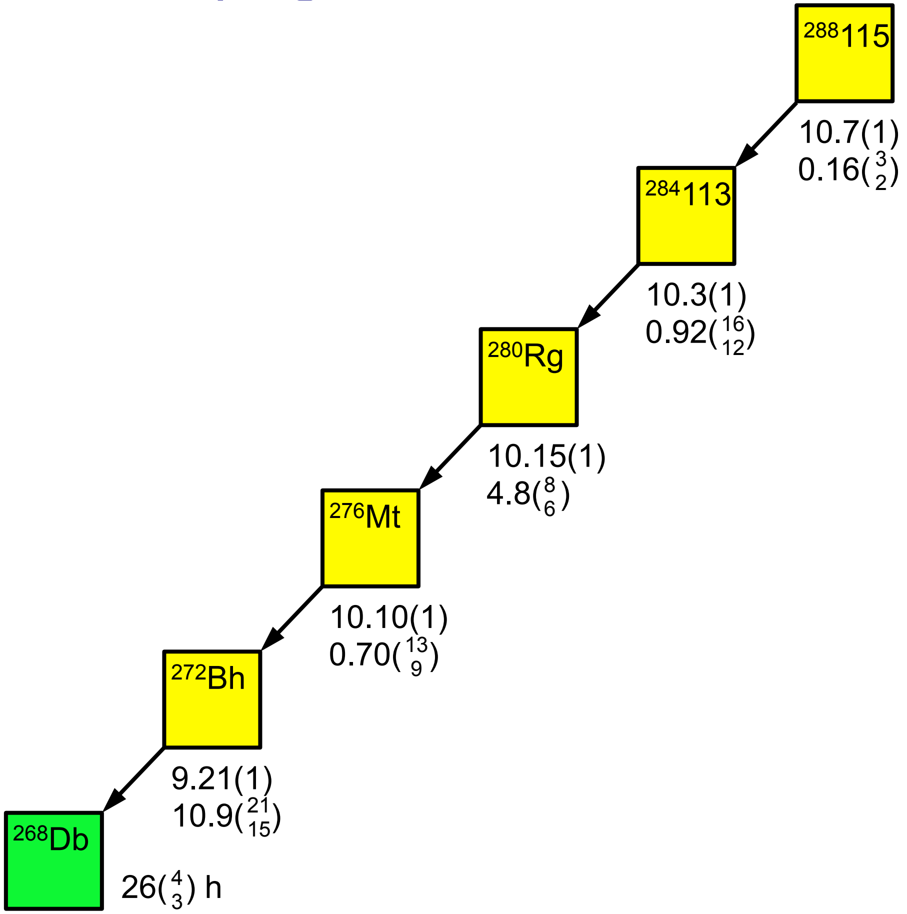
Results – $^{288}115$ (3n-channel)

22 chains (out of 30) of ours are compatible with the
31 chains (out of 37) associated with the 3n channel $^{288}115$
by Oganessian *et al*.

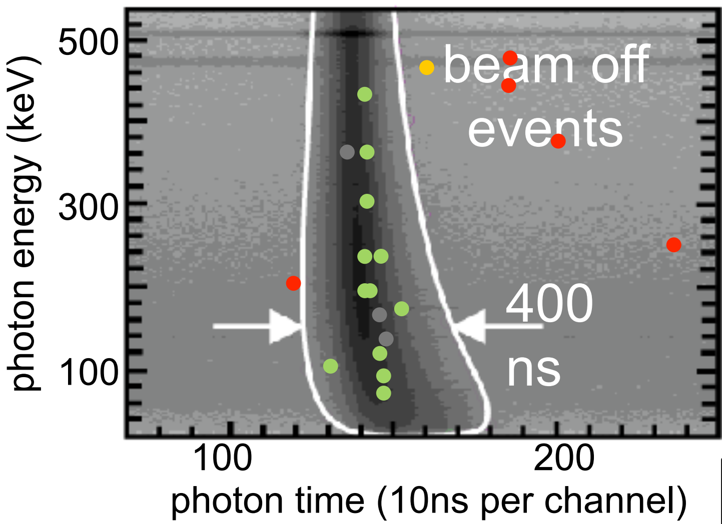


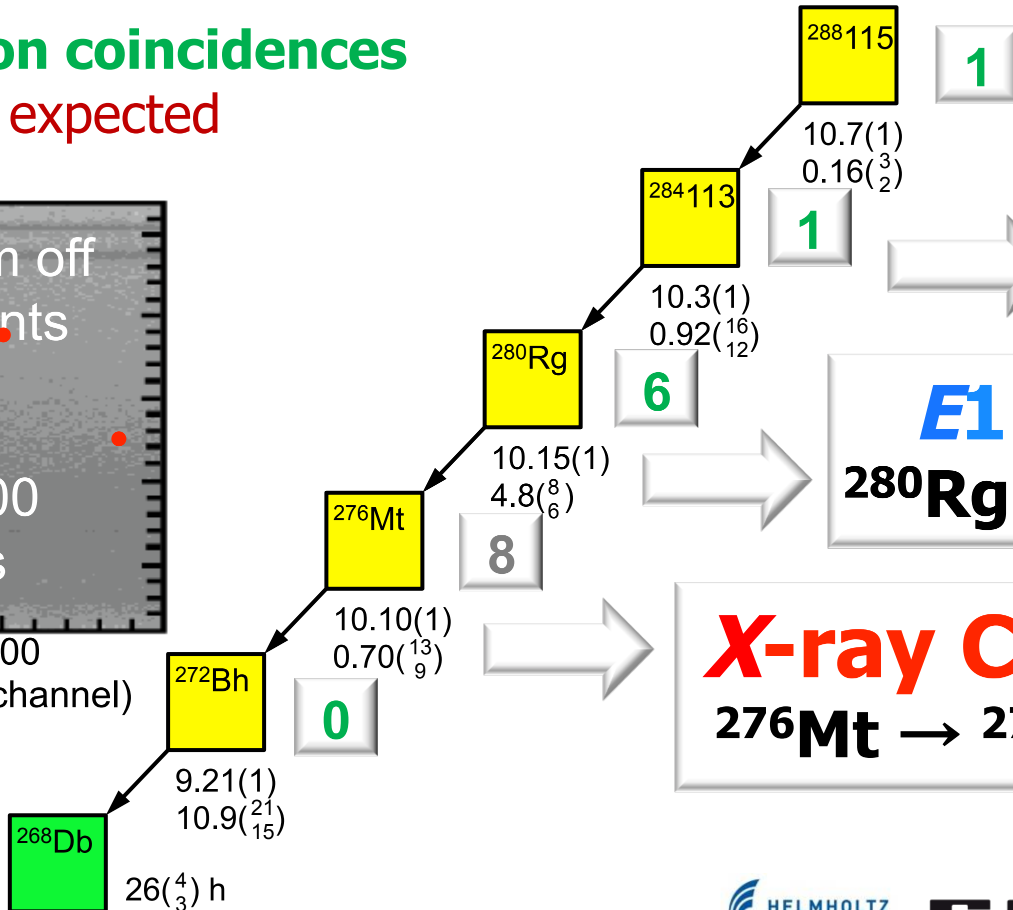
Courtesy D. Rudolph

Results – ^{288}115 (3n-channel)

22 chains (out of 30) of ours are compatible with the
31 chains (out of 37) associated with the 3n channel ^{288}115
by Oganessian *et al*.

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





Q_α
$T_{1/2}$

***E*1 Case**
^{280}Rg → ^{276}Mt

***X*-ray Case**
^{276}Mt → ^{272}Bh

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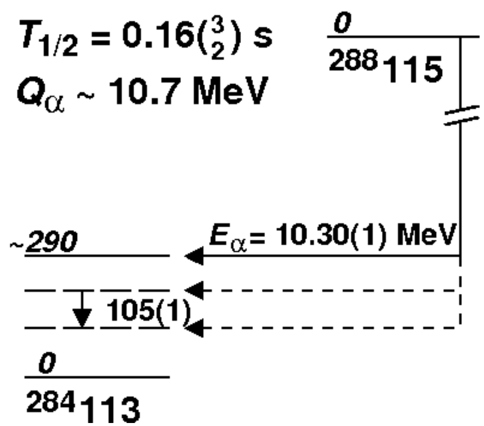
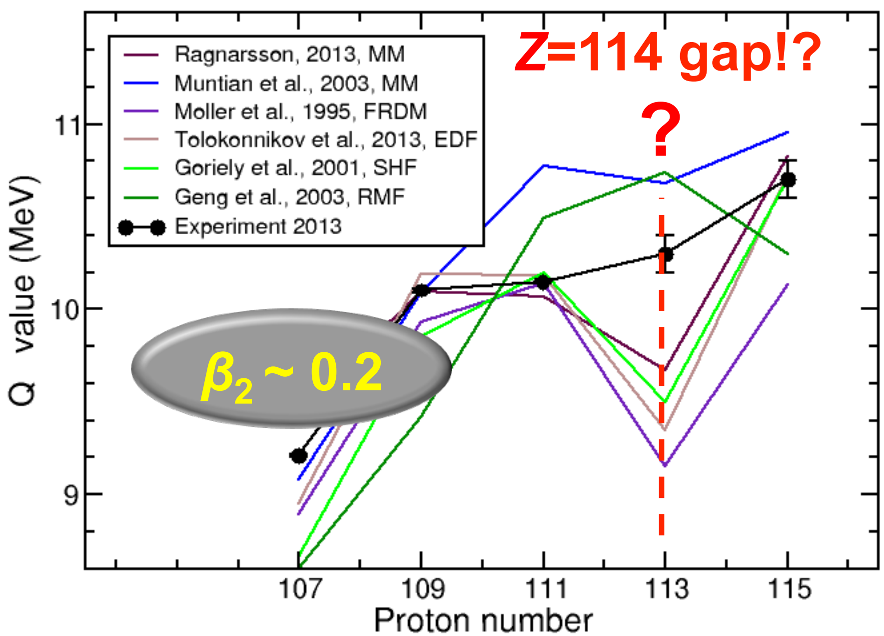
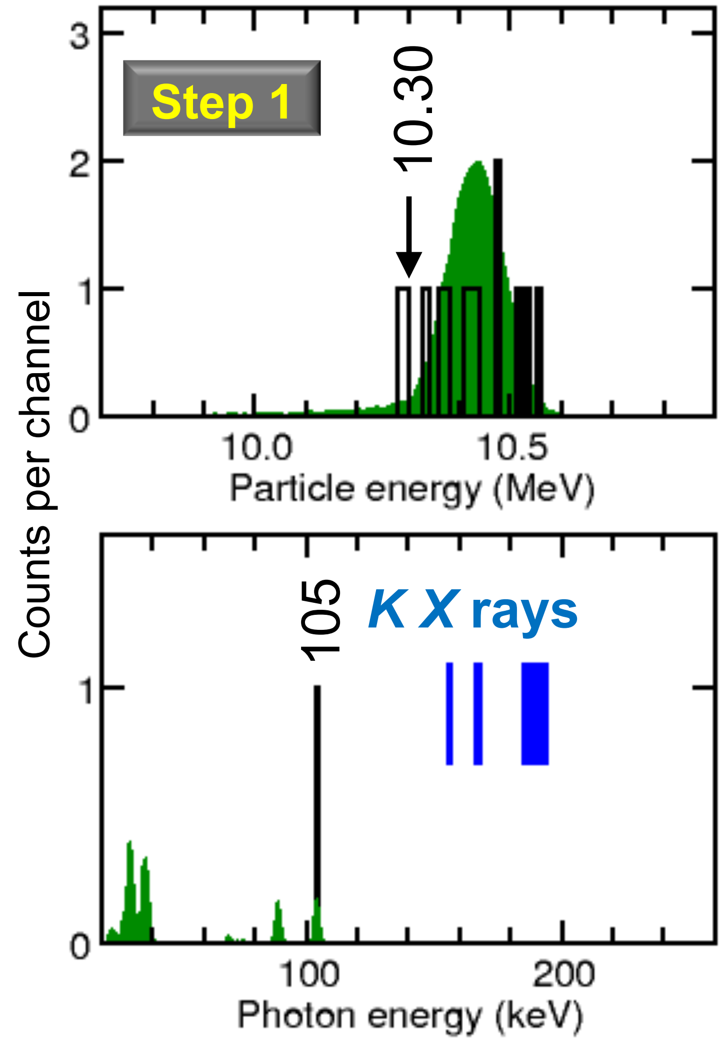
Results – $^{288}115$ (3n-chain)

Step 1







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

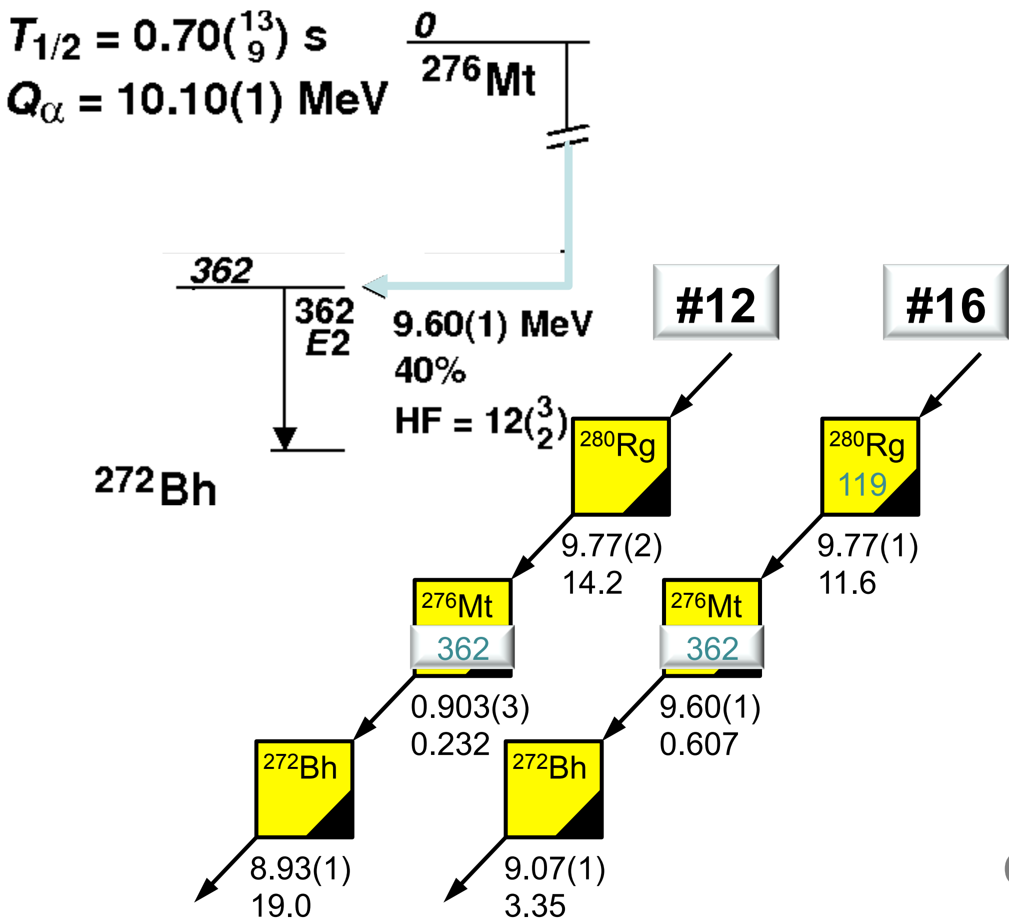
Courtesy D. Rudolph

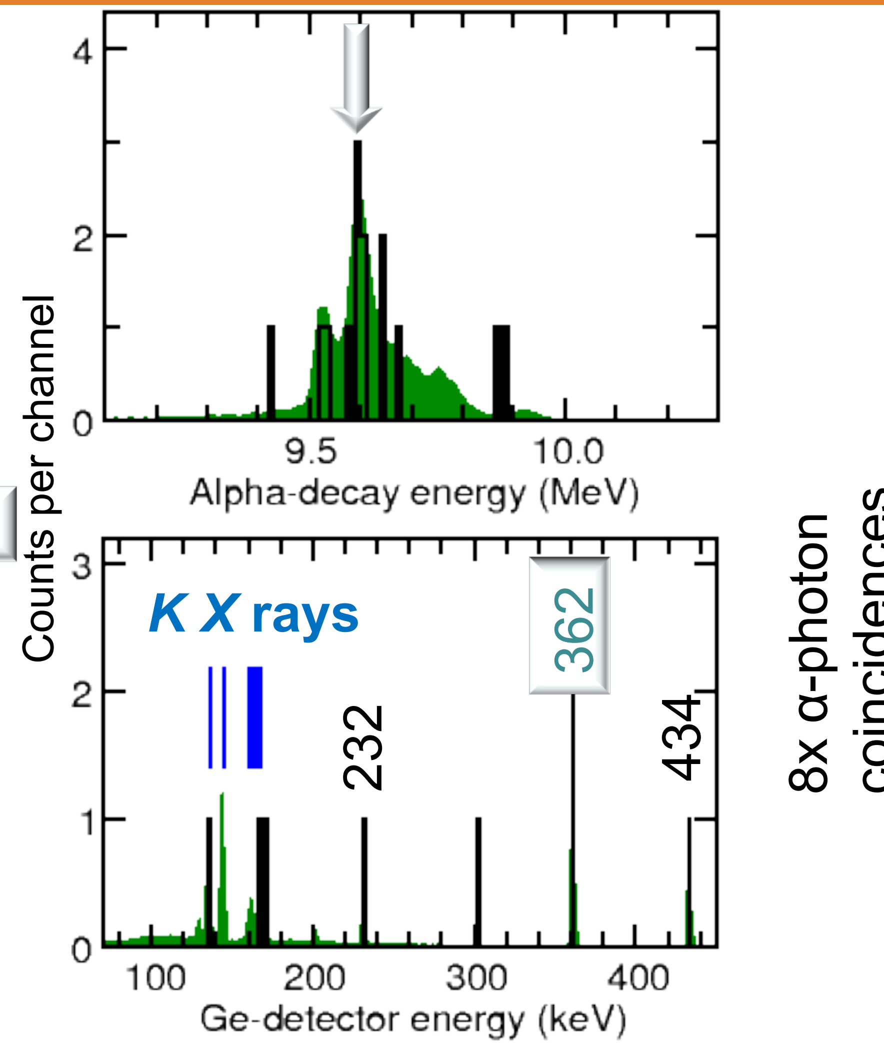
Results – ^{288}115 (3n-chain)

X-ray Case

^{276}Mt → ^{272}Bh

Step 4





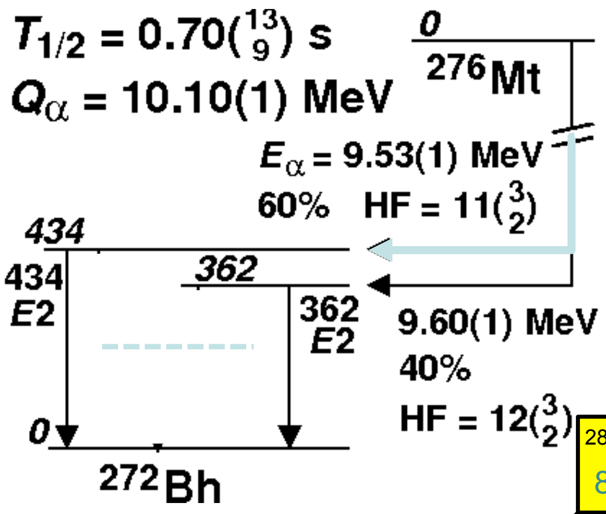
GEANT4 simulations: 100000 decays, normalized to number of α's

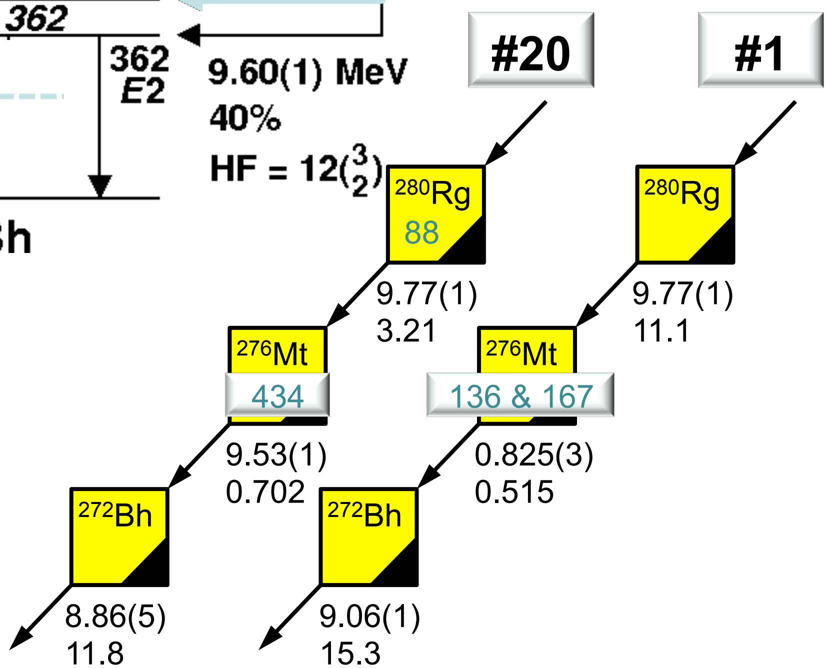
Results – ^{288}115 (3n-chain)

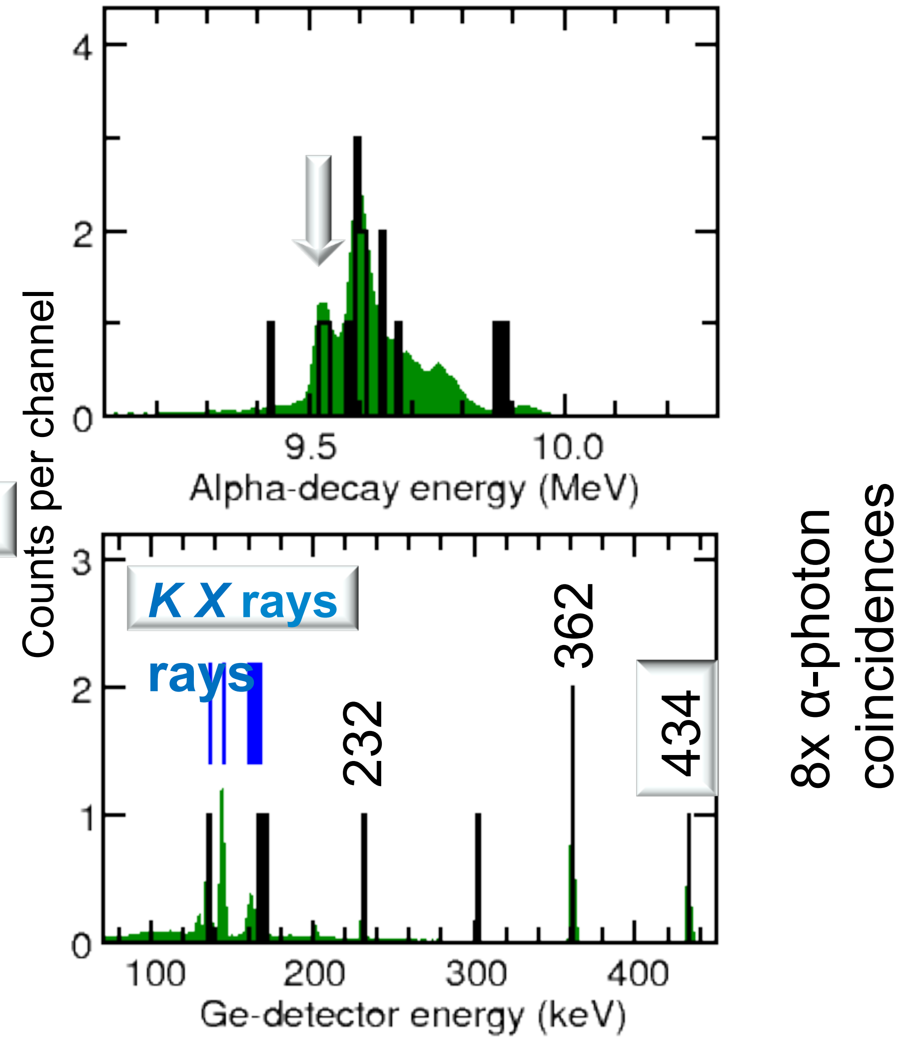
X-ray Case

$^{276}Mt \rightarrow {}^{272}Bh$

Step 4





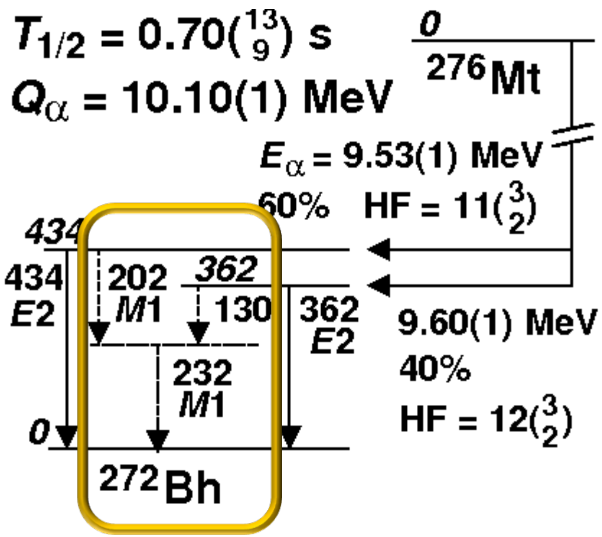


GEANT4 simulations: 100000 decays, normalized to number of α's

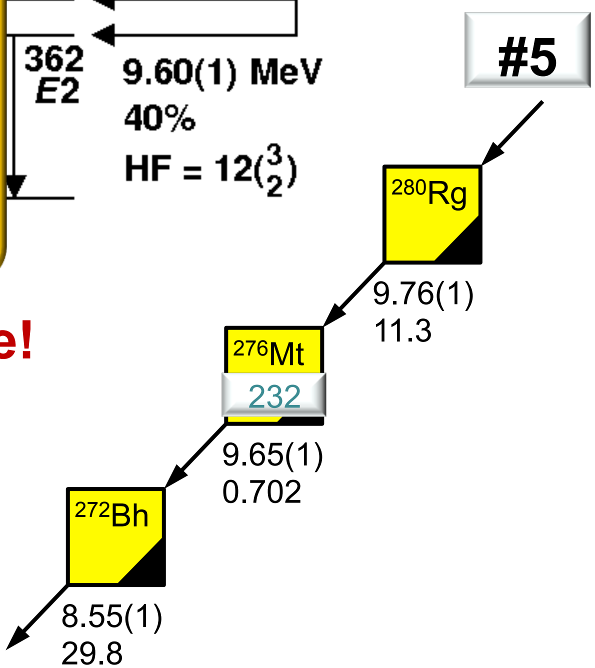
Results – $^{288}115$ (3n-chain)

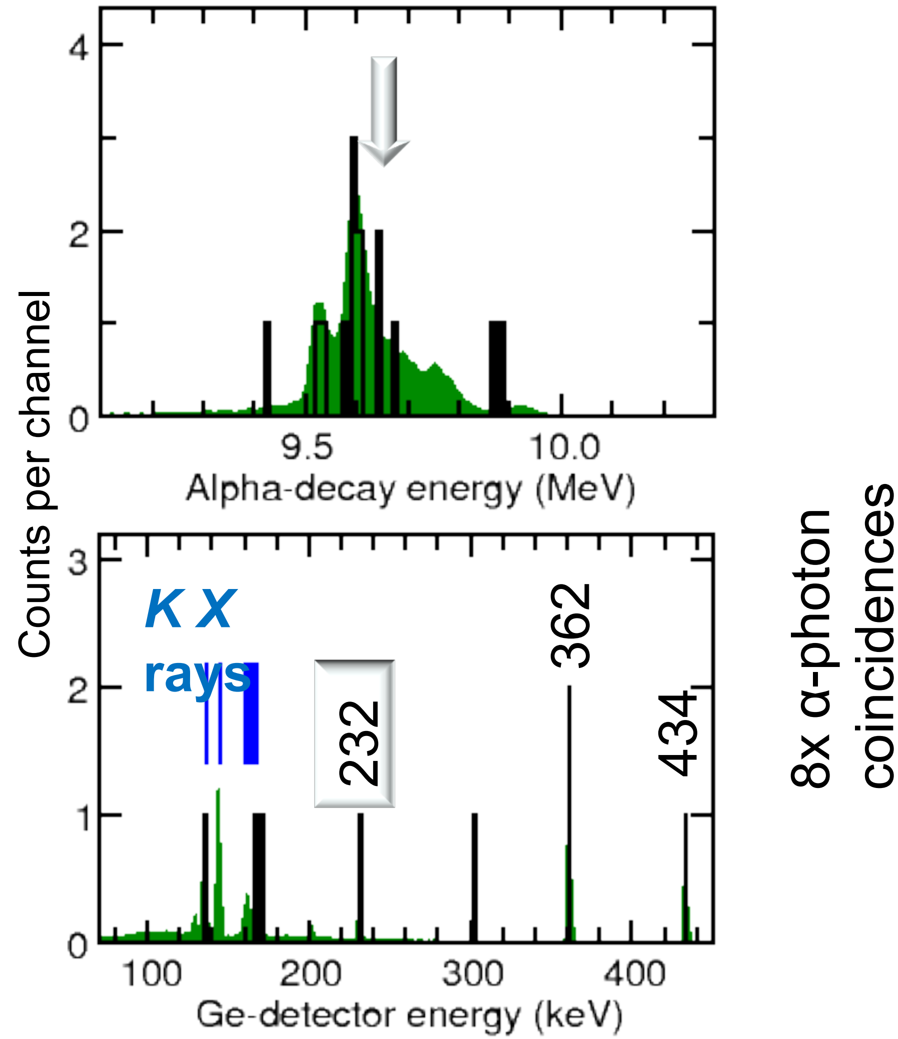
X-ray Case
$^{276}Mt \rightarrow {}^{272}Bh$

Step 4



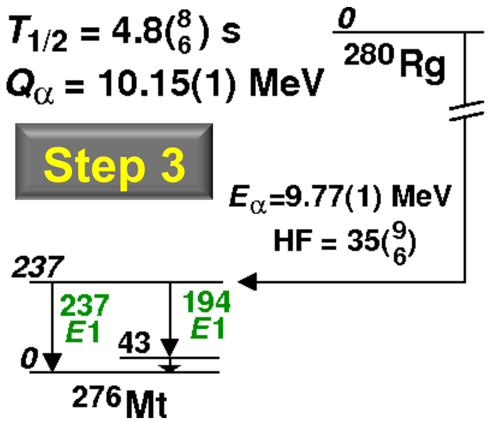
Tentative!





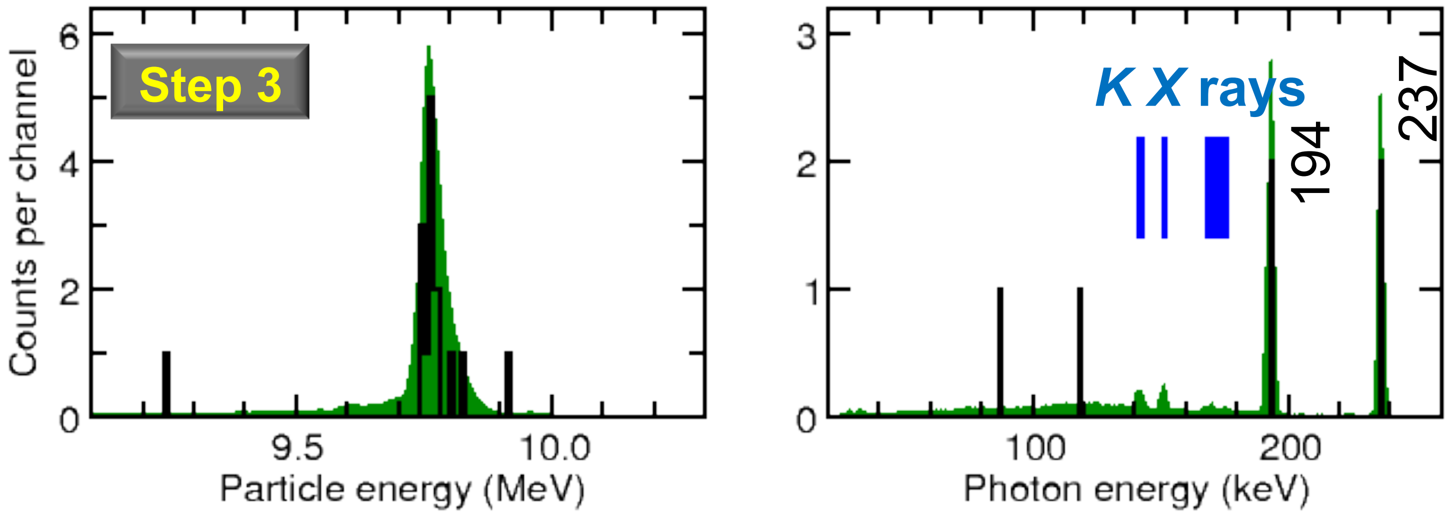
GEANT4 simulations: 100000 decays, normalized to number of α's

Results – $^{288}115$ (3n-chain)



*E*1 Case
$^{280}Rg \rightarrow {}^{276}Mt$

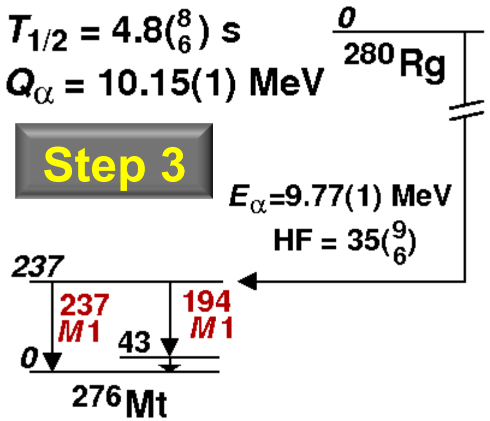
6x α-photon coincidences



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

Courtesy D. Rudolph

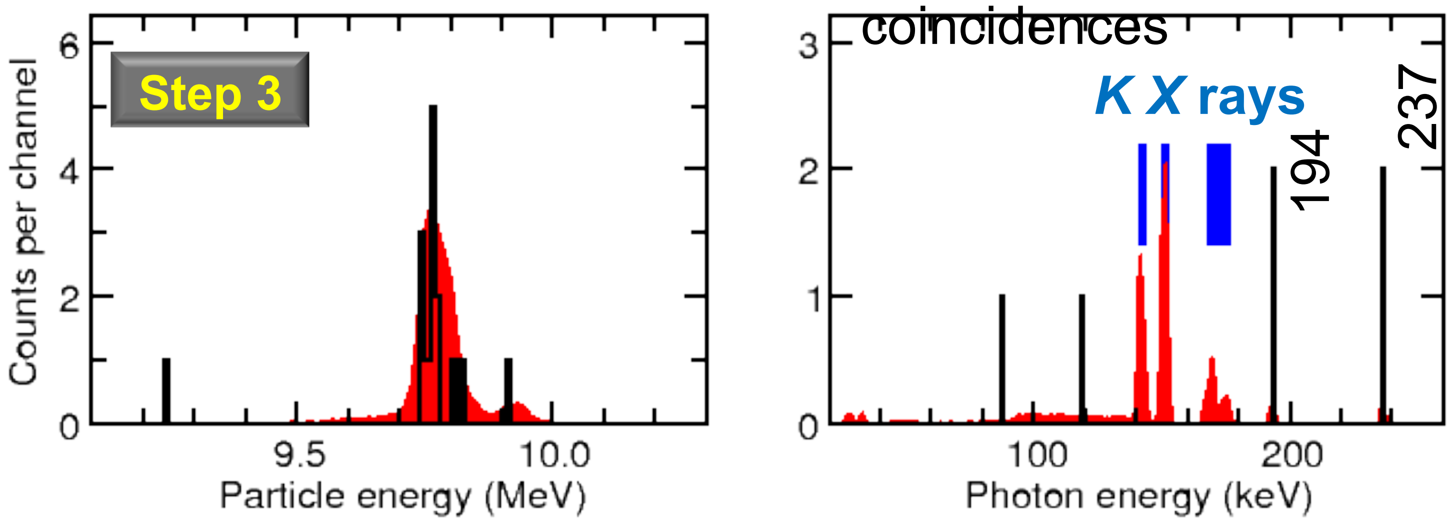
Results – ^{288}115 (3n-chain)



*M*1 Case

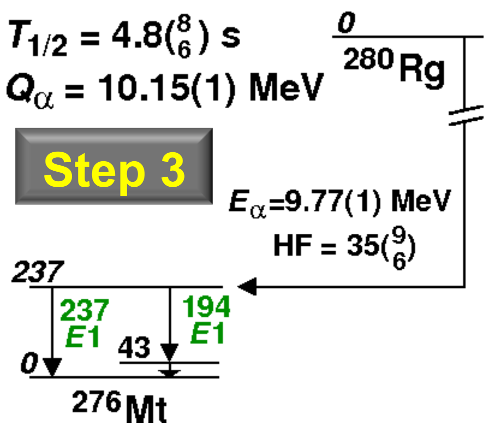
^{280}Rg → ^{276}Mt

IF Mother Nature had provided these transitions as *M*1 transitions, this would have been THE perfect fingerprinting case!



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

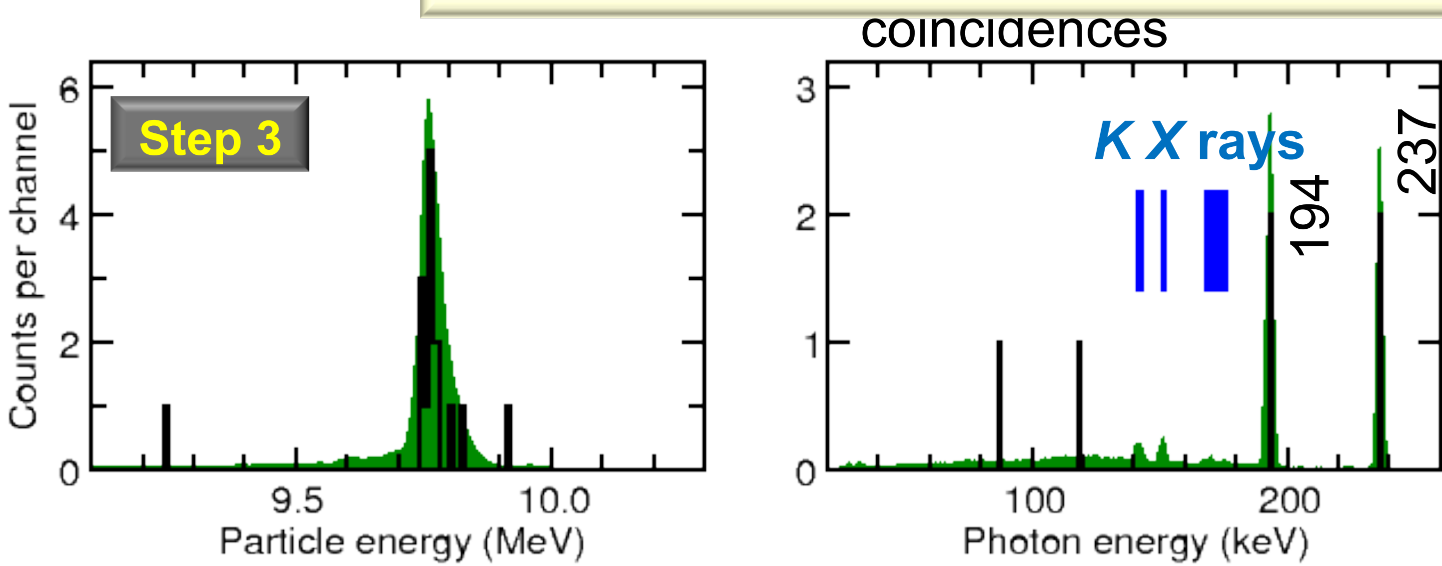
Results – $^{288}115$ (3n-chain)



E1 Case

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

The fact that these transitions are *E*1 transitions puts (seemingly) severe constraints on nuclear structure theory!



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

Summary and Outlook

- **GSI / Mainz: Broad SHE research program covering Nuclear Structure Studies, Atomic Physics and Chemistry investigations**
- High-precision mass measurements probe shell effects at N=152
- Decay spectroscopy allows detailed understanding of structure of SHN
- First a-g-spectroscopy of E115 performed, X-ray fingerprinting is feasible
- Event compatible with earlier reported data on E117 observed
- Focus 2011/12: Search for new elements 119 & 120
  - ^{249}Cf(^{50}Ti,xn)$^{299-x}$120: one-event TASCA limit is <160 fb
  - ^{249}Bk(^{50}Ti,xn)$^{299-x}$119: one-event TASCA limit is <70 fb
- Progressing beyond Z=118 necessitates 10 fb sensitivity
- Additional gain in sensitivity by cw-linac possible (beam intensity x 10)
- Laser resonance ionization spectroscopy of ^{254}No planned in 2014

Thank you for your attention!

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