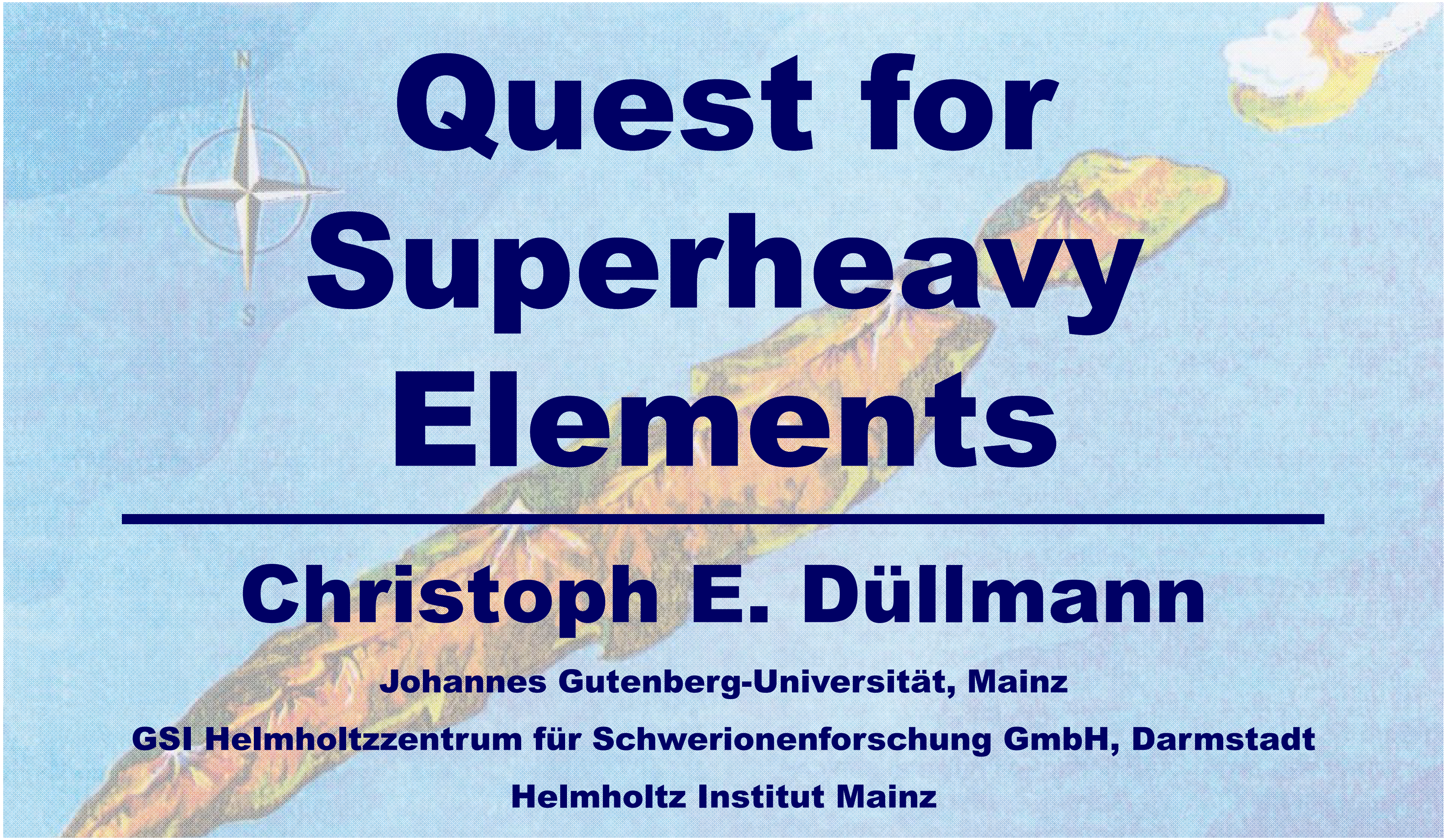
www.superheavies.de
c.e.duellmann@gsi.de



Quest for Superheavy Elements

Christoph E. Düllmann

Johannes Gutenberg-Universität, Mainz

GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt

Helmholtz Institut Mainz

Ecole Joliot-Curie "Nucleus through the looking glass – High intensity stable and ISOL beam frontier"
La Villa Clythia – Fréjus – France – September 30-October 05, 2012

What's on the menu this week?

Lesson 1:

-Discovery of the transuranium elements: Z=93 - 112

-Stability of superheavy elements I

Lesson 2:

-Discovery of the transuranium elements: Z=113- ...

-Stability of superheavy elements II

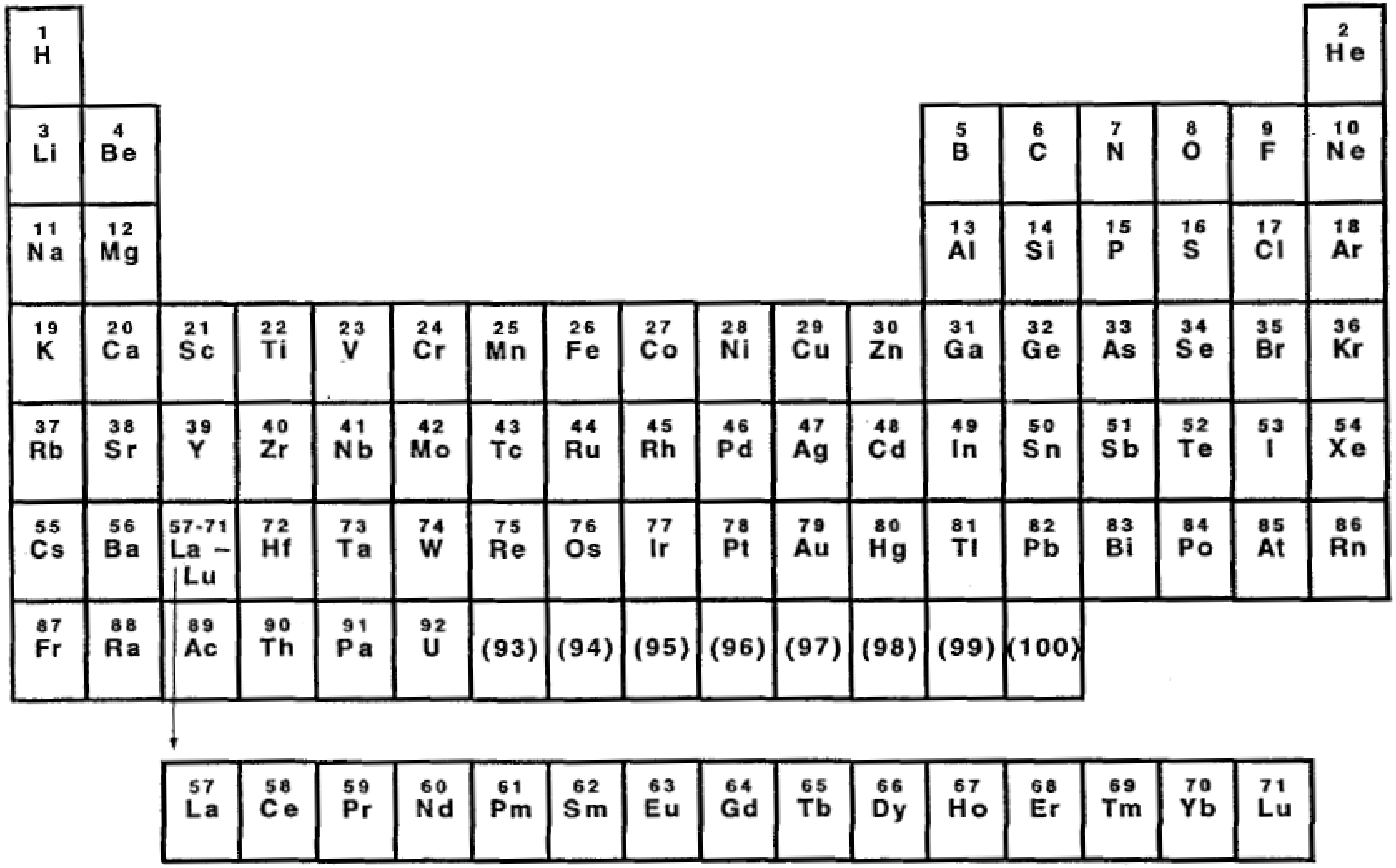
Lesson 3:

-Reactions: synthesis of SHE

-Search for new elements at GSI

Introduction: looking back a few decades...

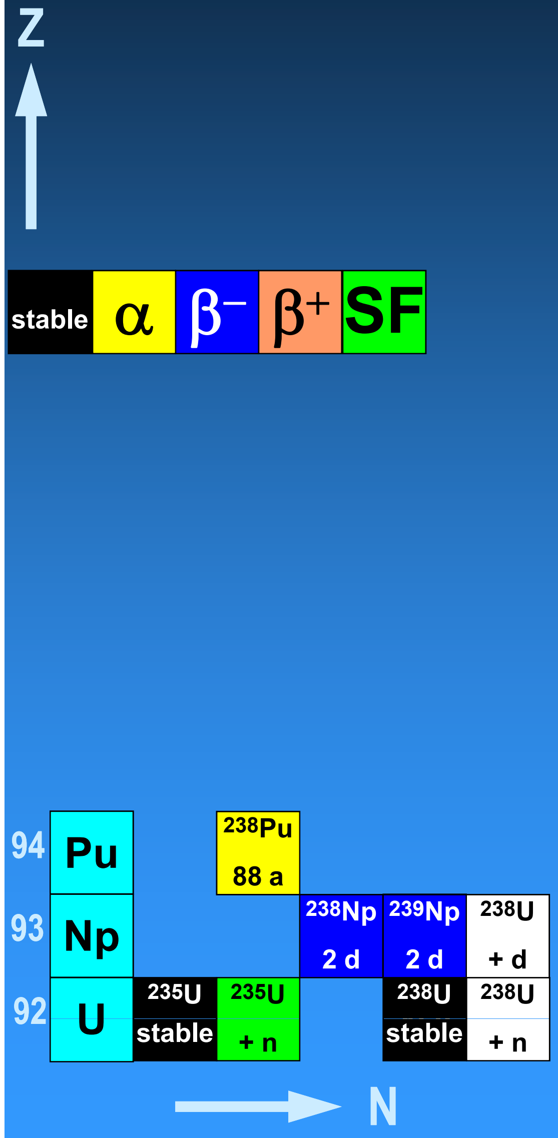
The Periodic Table 1939



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 – Lu	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	90 Th	91 Pa	92 U	(93)	(94)	(95)	(96)	(97)	(98)	(99)	(100)				
		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	

Np: Milking of U-daughter; not Re-like

Pu: not Os-like

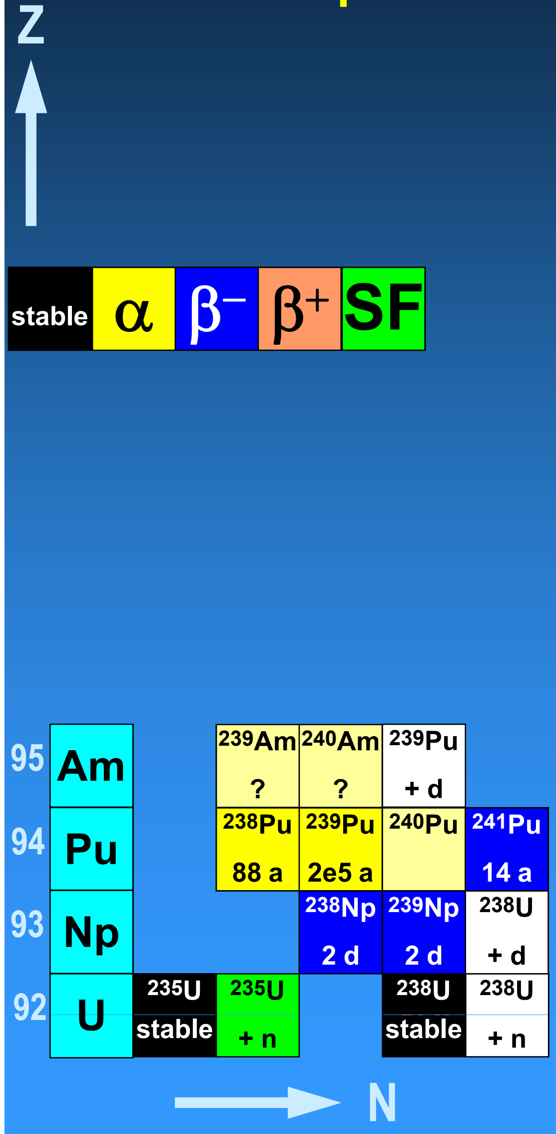


3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Sc	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
Ac	Th	Pa	U	Np	Pu									
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

Np: Milking of U-daughter; not Re-like

Pu: not Os-like ⇒ Uranide-concept

E95 attempts fail



95	**Am**		^{239}Am ?	^{240}Am ?	^{239}Pu + d	
94	**Pu**		^{238}Pu 88 a	^{239}Pu 2e5 a	^{240}Pu	^{241}Pu 14 a
93	**Np**			^{238}Np 2 d	^{239}Np 2 d	^{238}U + d
92	**U**	^{235}U stable	^{235}U + n		^{238}U stable	^{238}U + n

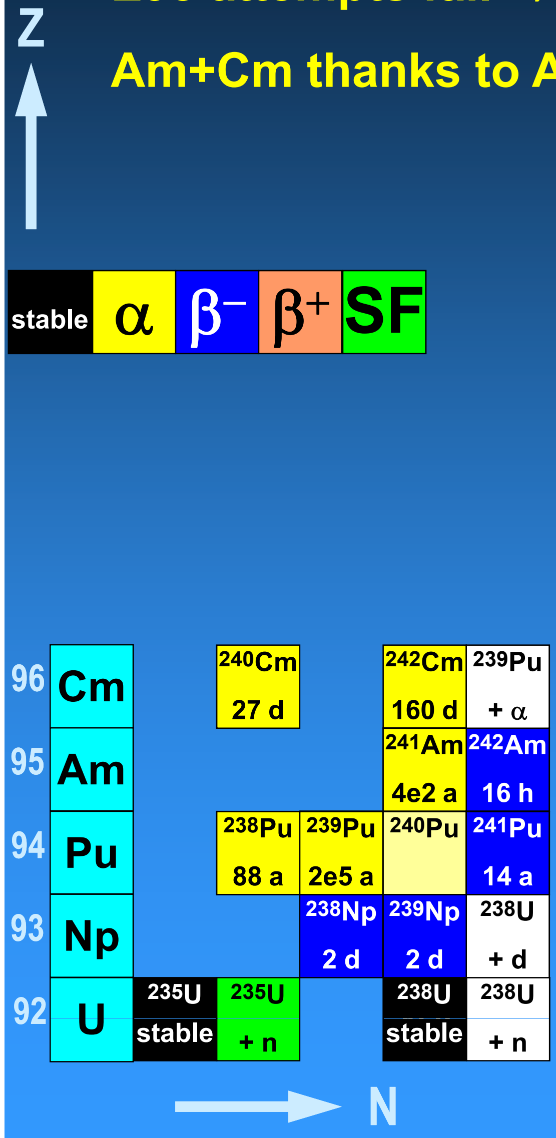
	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Sc	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
Ac	Th	Pa												
			U	Np	Pu	95								
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

Np: Milking of U-daughter; not Re-like

Pu: not Os-like ⇒ Uranide-concept

E95 attempts fail ⇒ Actinide concept

Am+Cm thanks to An concept



3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Sc	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
Ac														

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm							

Np: Milking of U-daughter; no

Pu: not Os-like ⇒ Uranide-cor

E95 attempts fail ⇒ Actinide c

Am+Cm thanks to An concept

Bk+heavier: Chromatographic

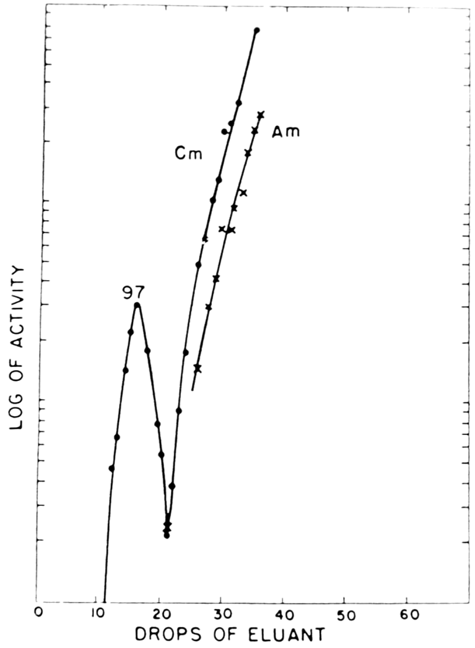
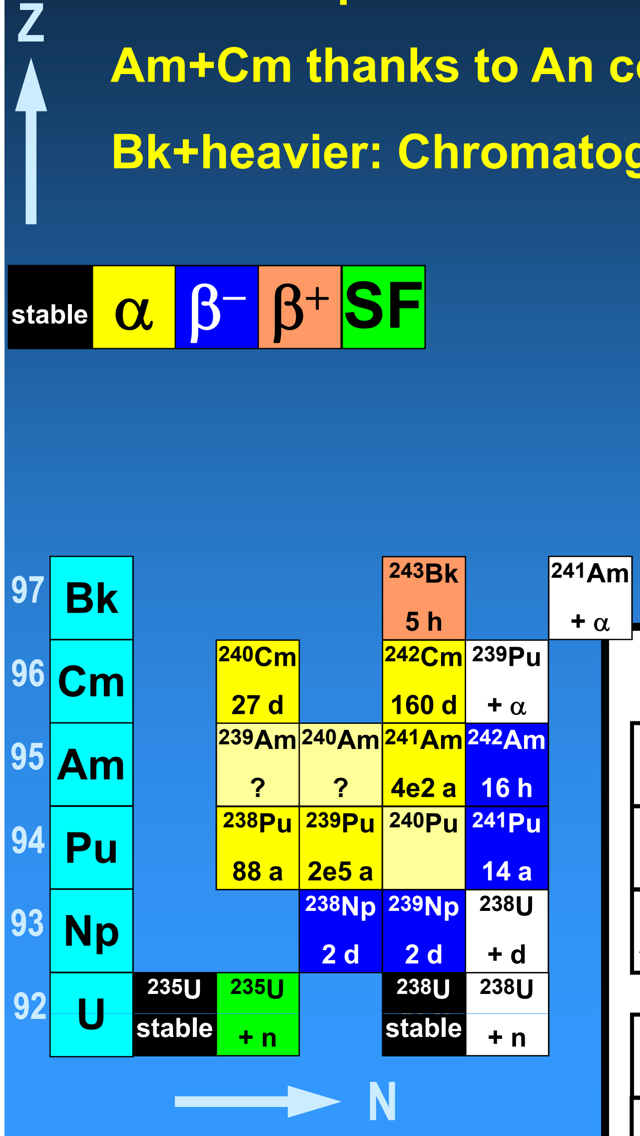


Fig. 5.3. Original elution data corresponding to the discovery of berkelium (^{243}Bk); S.G. Thompson, A. Ghiorso, and G.T. Seaborg, December 19, 1949; Dowex-50 eluted with citrate at 87°C.



3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Sc	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
Ac														

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk						

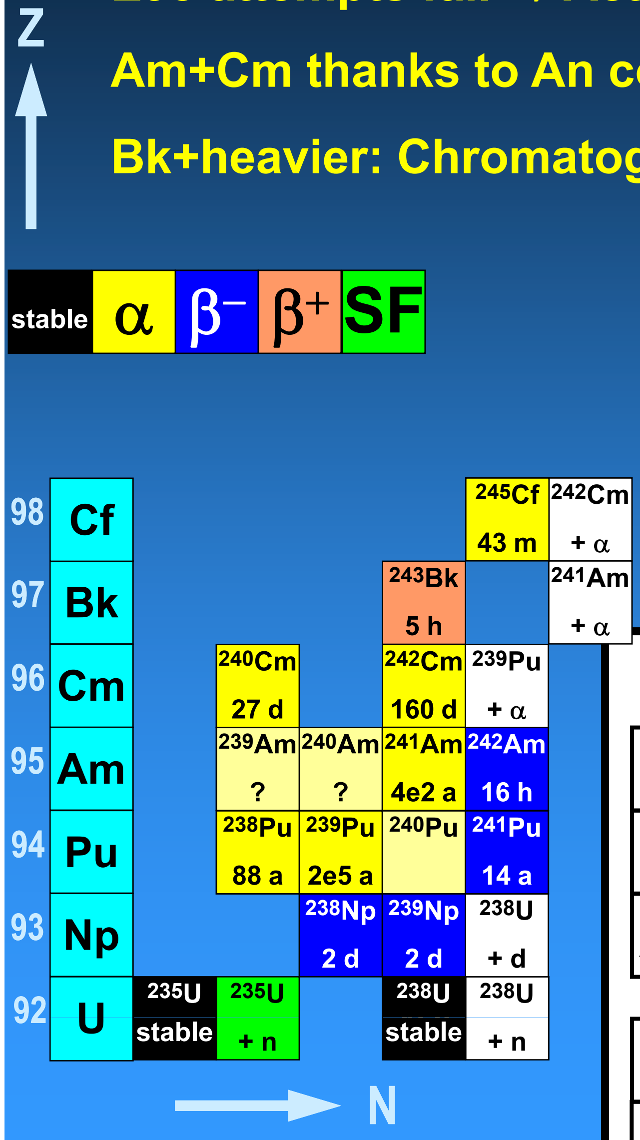
Np: Milking of U-daughter; not Re-like

Pu: not Os-like ⇒ Uranide-concept

E95 attempts fail ⇒ Actinide concept

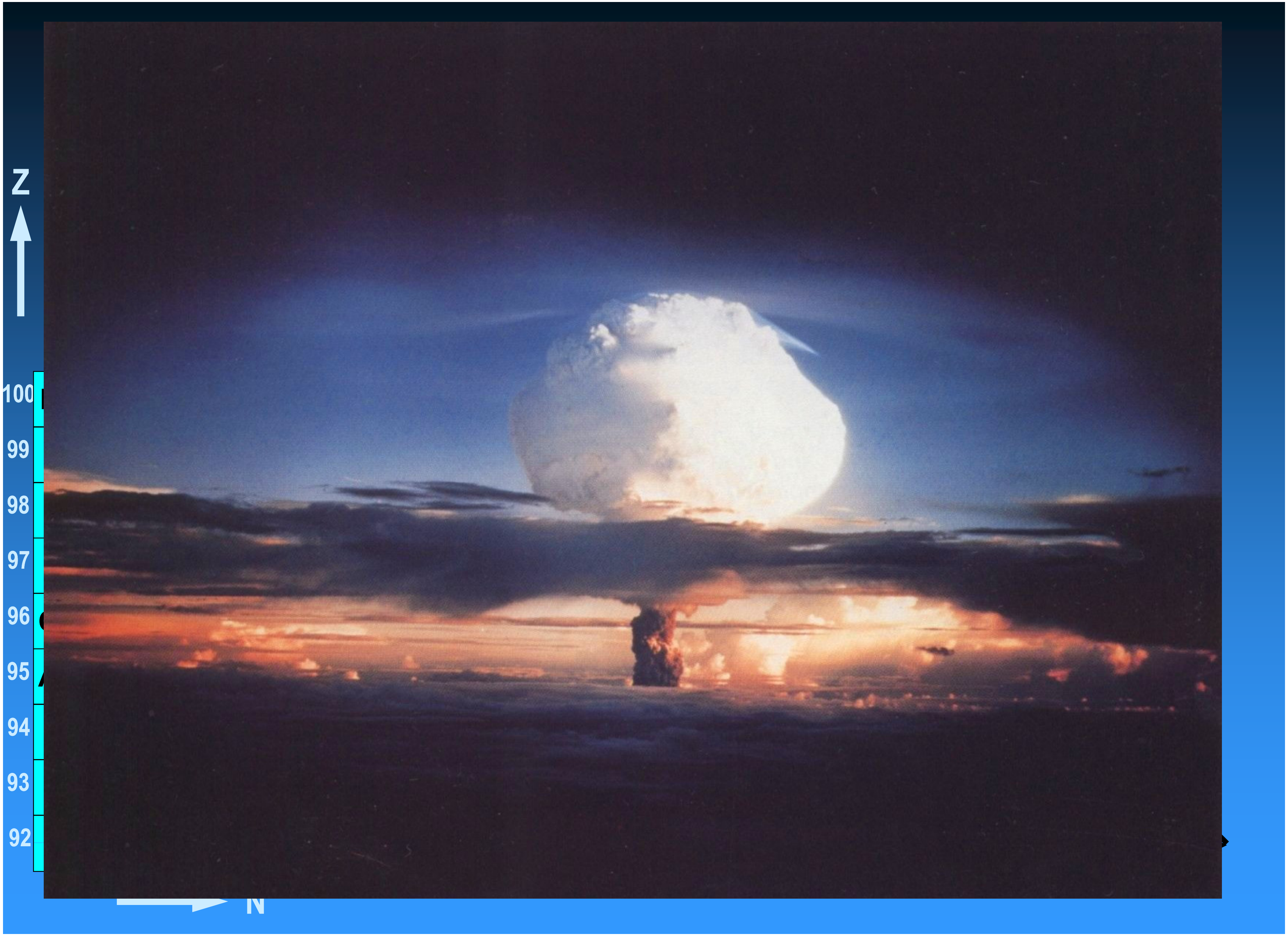
Am+Cm thanks to An concept

Bk+heavier: Chromatographic separation of An



3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Sc	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
Ac														

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf					


Z
100
99
98
97
96
95
94
93
92
N

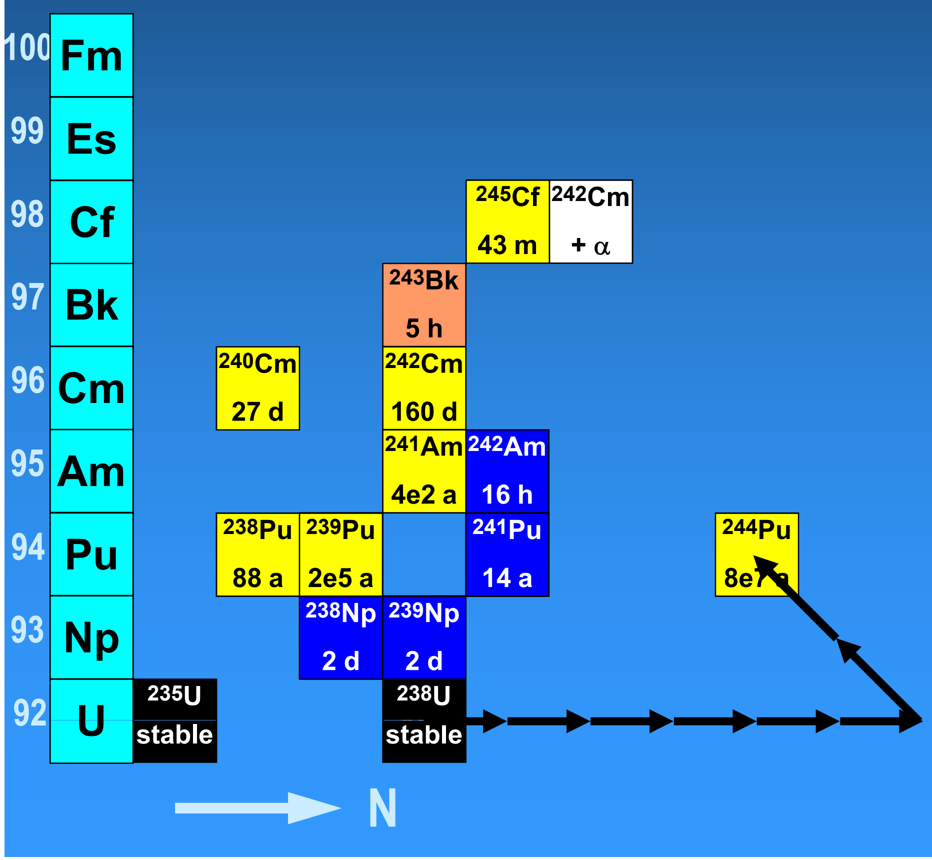
Np: Milking of U-daughter; not Re-like

Pu: not Os-like ⇒ Uranide-concept

E95 attempts fail ⇒ Actinide concept

Am+Cm thanks to An concept

Bk+heavier: Chromatographic separation of An



Np: Milking of U-daughter; not Re-like

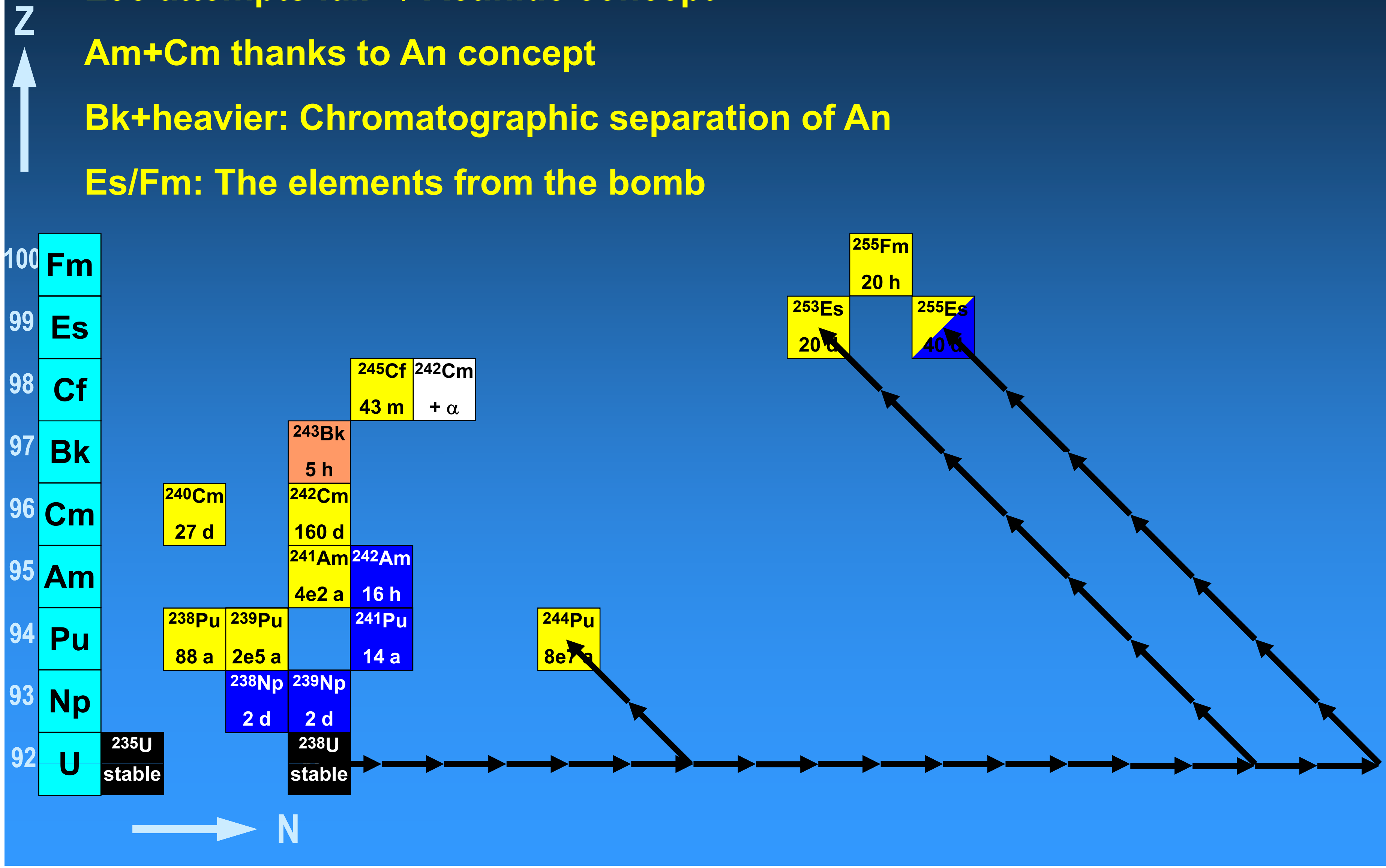
Pu: not Os-like ⇒ Uranide-concept

E95 attempts fail ⇒ Actinide concept

Am+Cm thanks to An concept

Bk+heavier: Chromatographic separation of An

Es/Fm: The elements from the bomb



Np: Milking of U-daughter; not Re-like

Pu: not Os-like ⇒ Uranide-concept

E95 attempts fail ⇒ Actinide concept

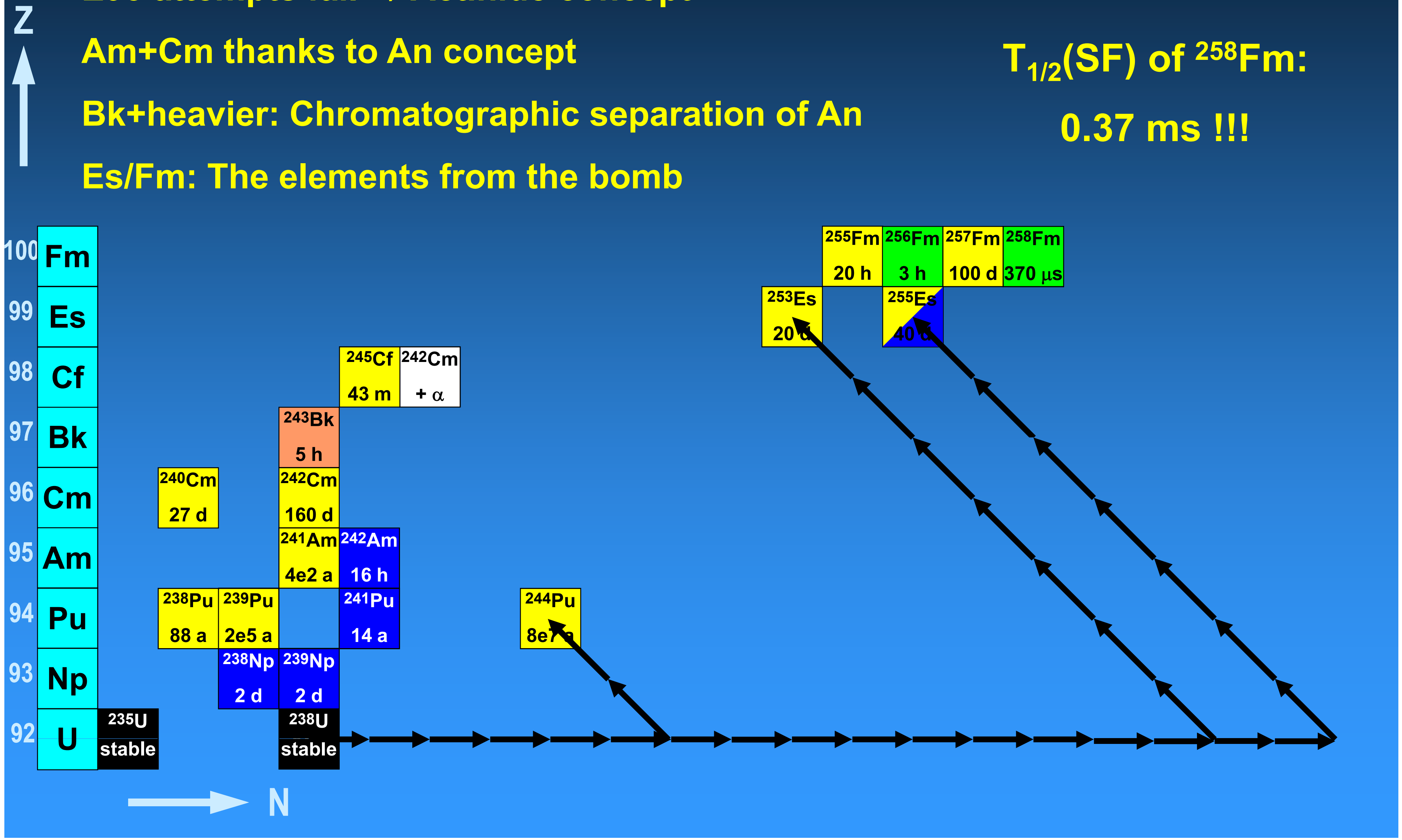
Am+Cm thanks to An concept

Bk+heavier: Chromatographic separation of An

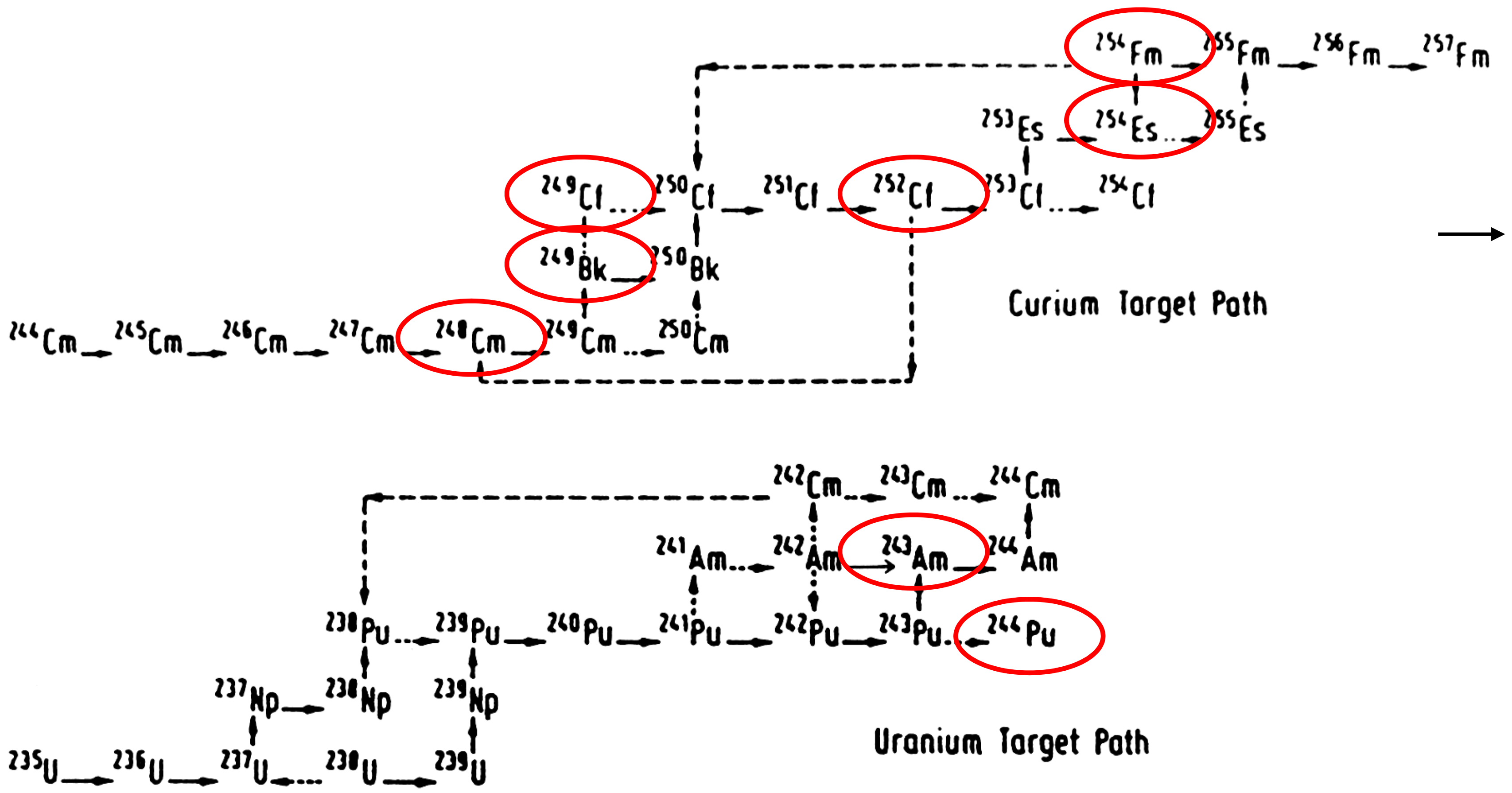
Es/Fm: The elements from the bomb

$T_{1/2}$(SF) of ^{258}Fm:

0.37 ms !!!



Production of transuranium nuclides in a high flux reactor



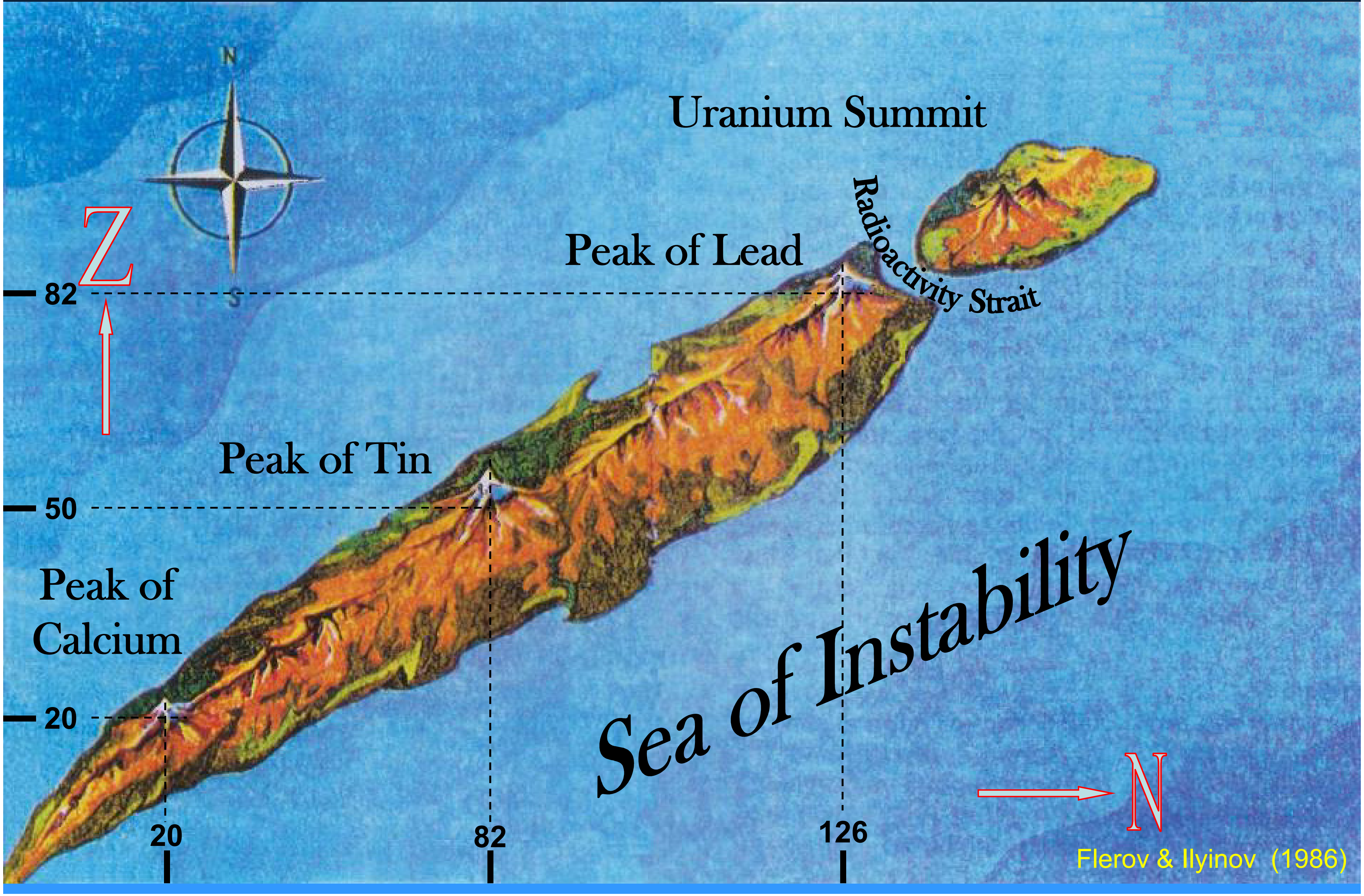
$^{257}\mathrm{Fm} \xrightarrow{n} {}^{258}\mathrm{Fm}$ (SF, 0.38 ms !)

Fm is the heaviest element that can be produced in a reactor

Lessons learned

- Elements up to Fm can be produced in a reactor, heavier ones not
- Reactor-produced long-lived nuclides: targets for accelerator based experiments. Heaviest targets: $^{248}_{96}$Cm, $^{249}_{97}$Bk, $^{249}_{98}$Cf ($^{253}_{99}$Es)
- Nuclear properties can change dramatically by adding/removing one single nucleon
- Correct assumptions of the structure of the Periodic Table needed for chemical experiments

Map of the Nuclear Landscape

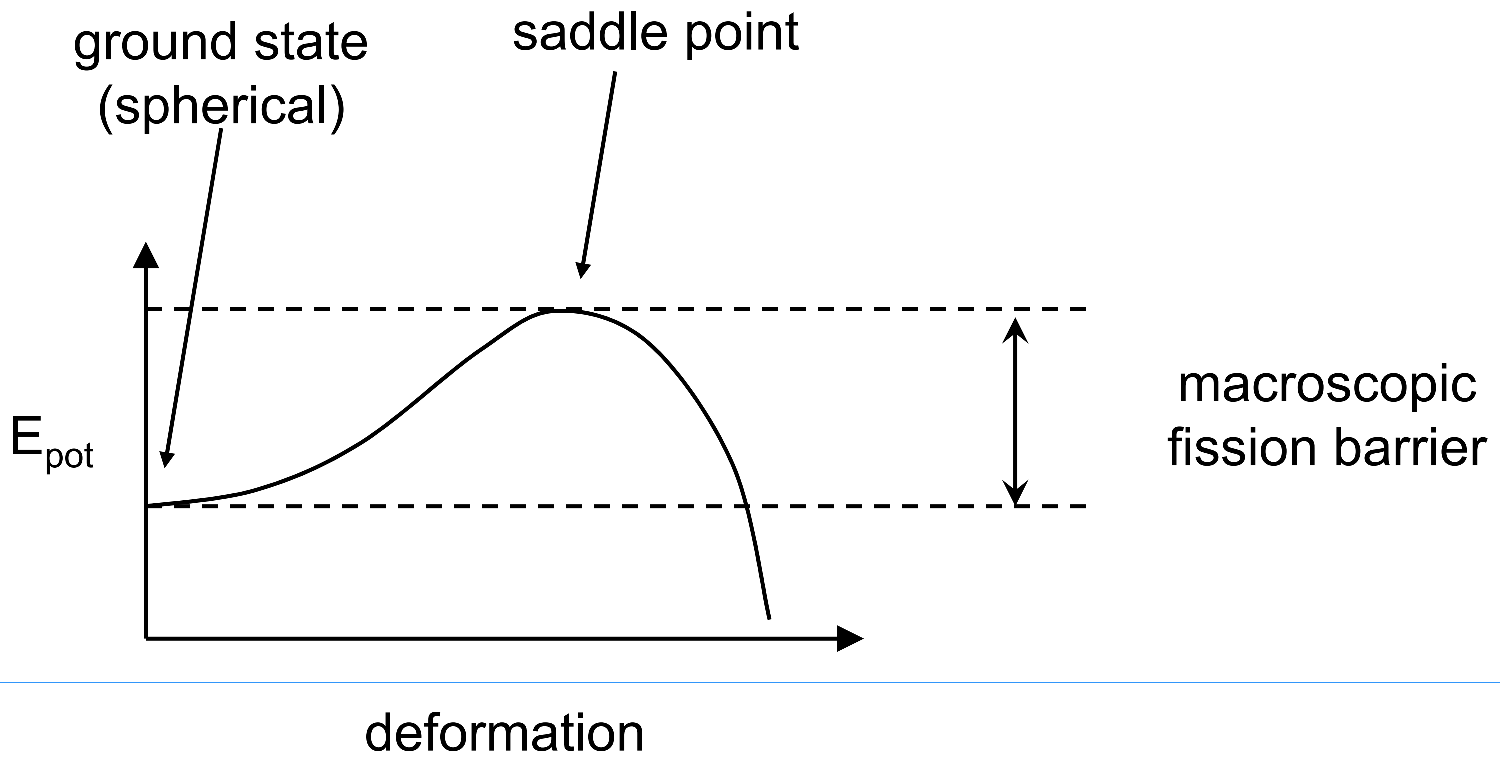


The Fission Barrier

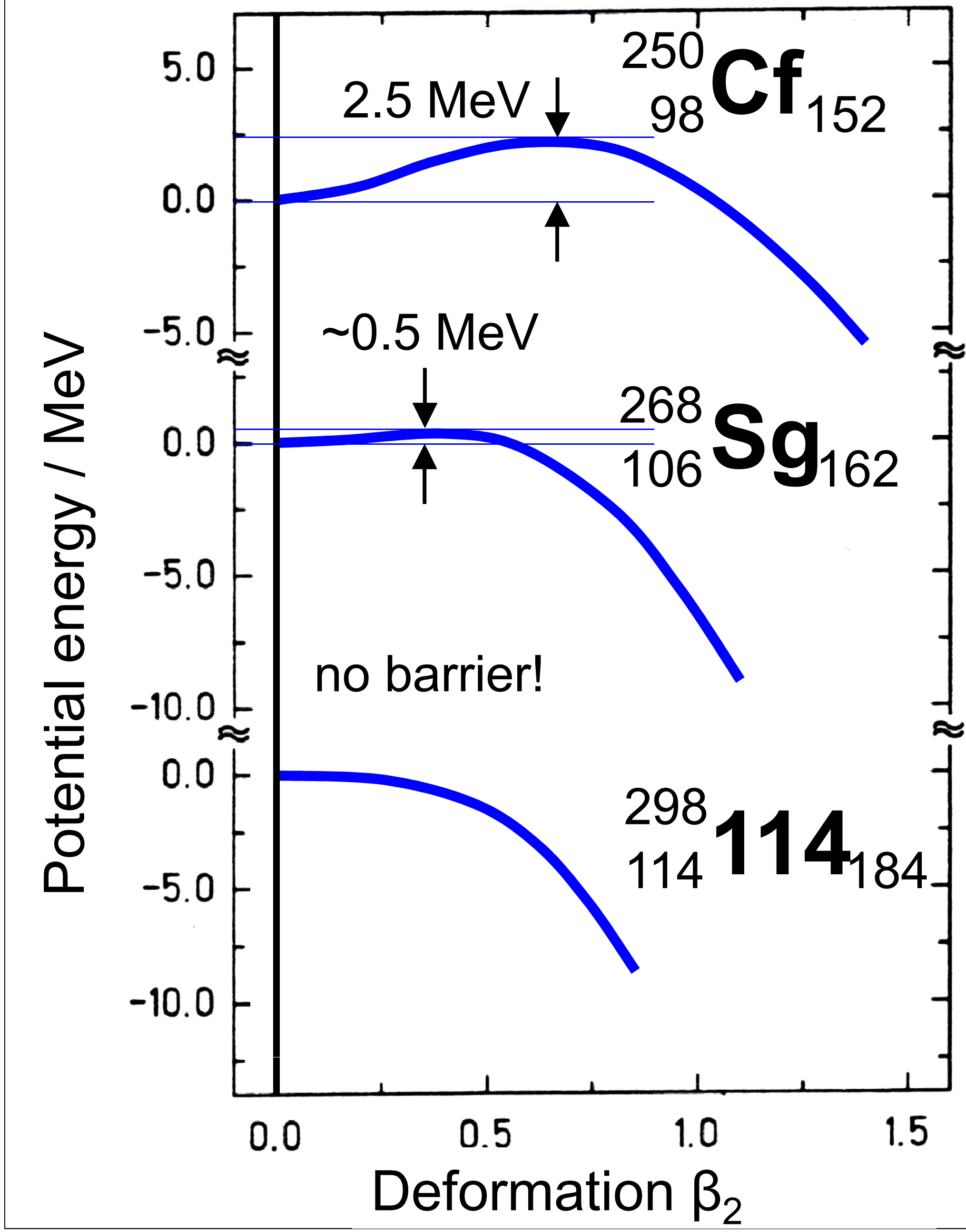
Liquid drop model includes two deformation-dependent terms:

The Coulomb energie decreases with increasing deformation due to the larger average proton-proton distance

The surface energy increases with increasing deformation as the sphere is the body with minimum surface for a given volume



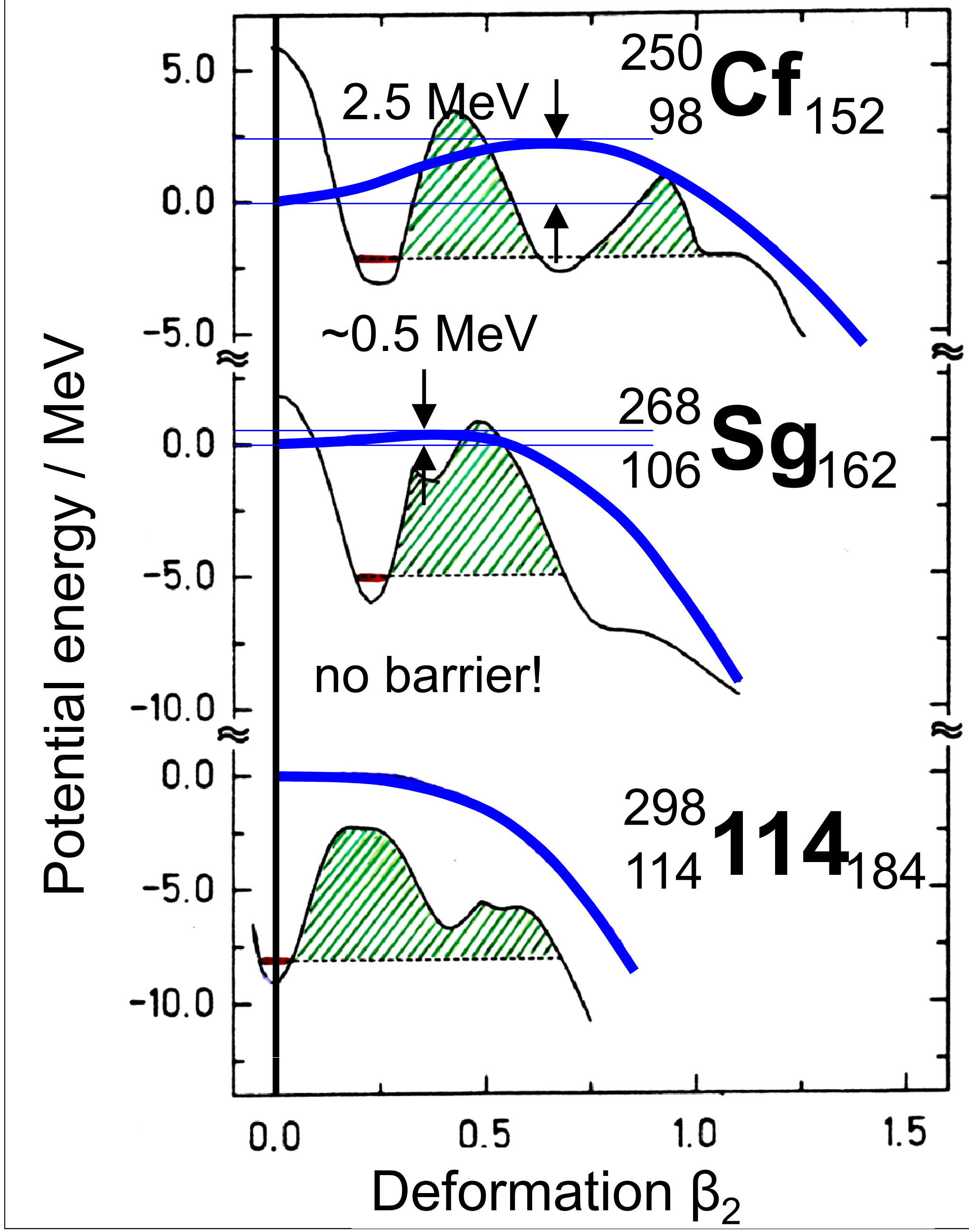
Influence of shell effects on fission barrier



▬ macroscopic barrier:

Disappears at Z ~ 104!

Influence of shell effects on fission barrier



macroscopic barrier:

Disappears at Z ~ 104!

with shell structure:

spherical ↔ deformed ground state

fission barrier is also > 0 for elements with Z ≥104.

some fission barriers have complicated shapes, multiply-humped ⇒ fission isomers!

elements that exist only thanks to shell effects:

superheavy elements

Influence of Shell Effects on SF Half-Lives

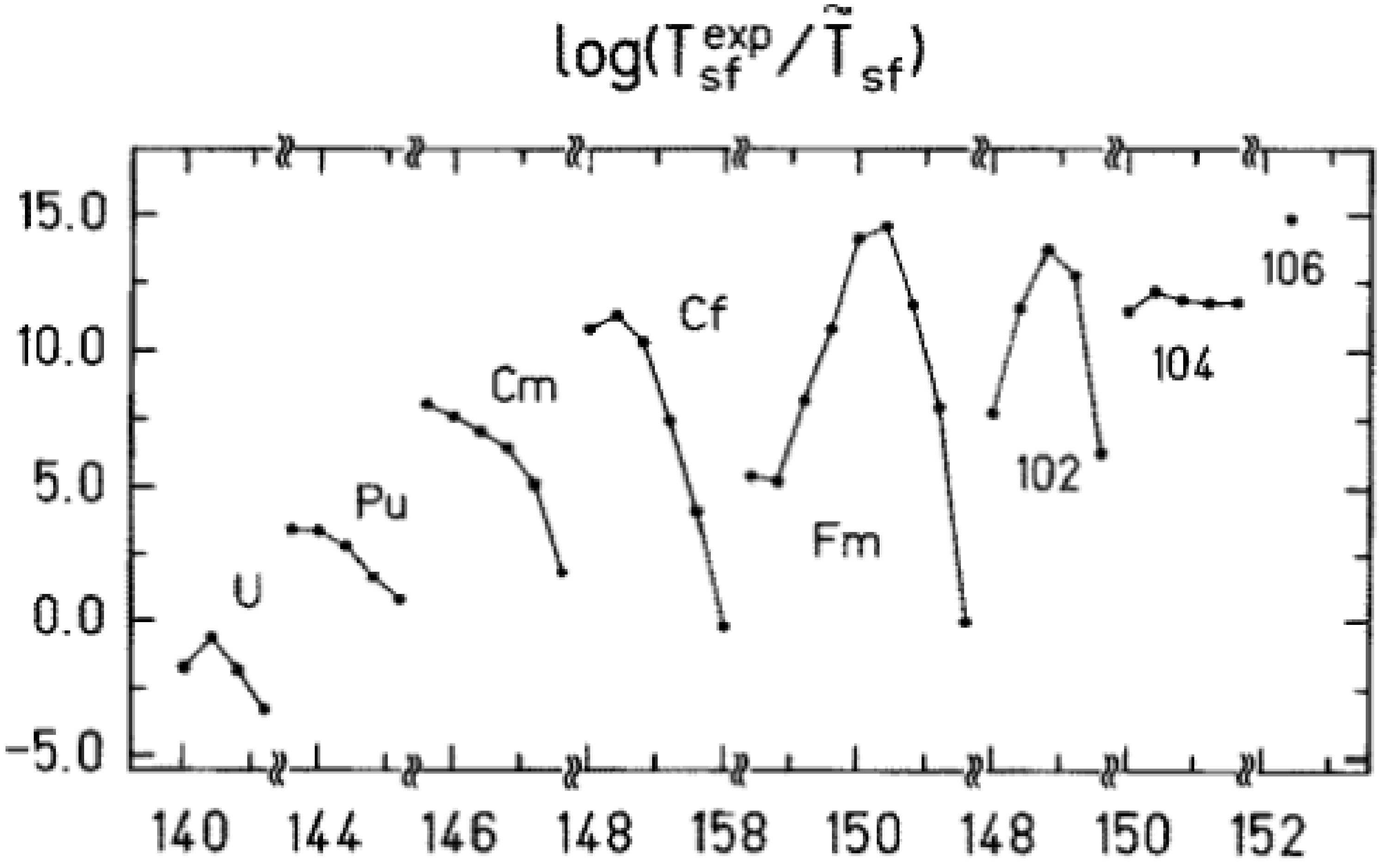
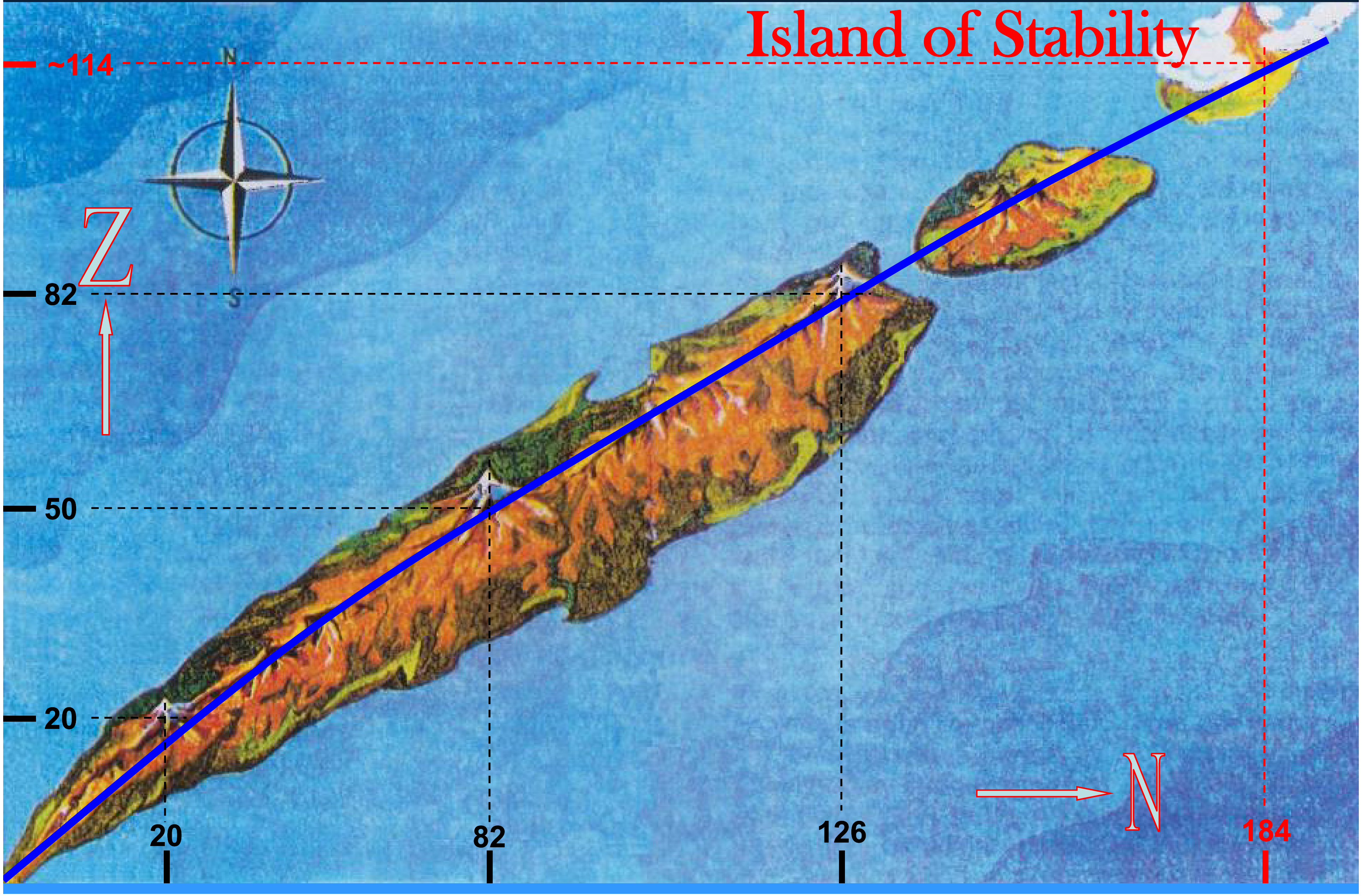
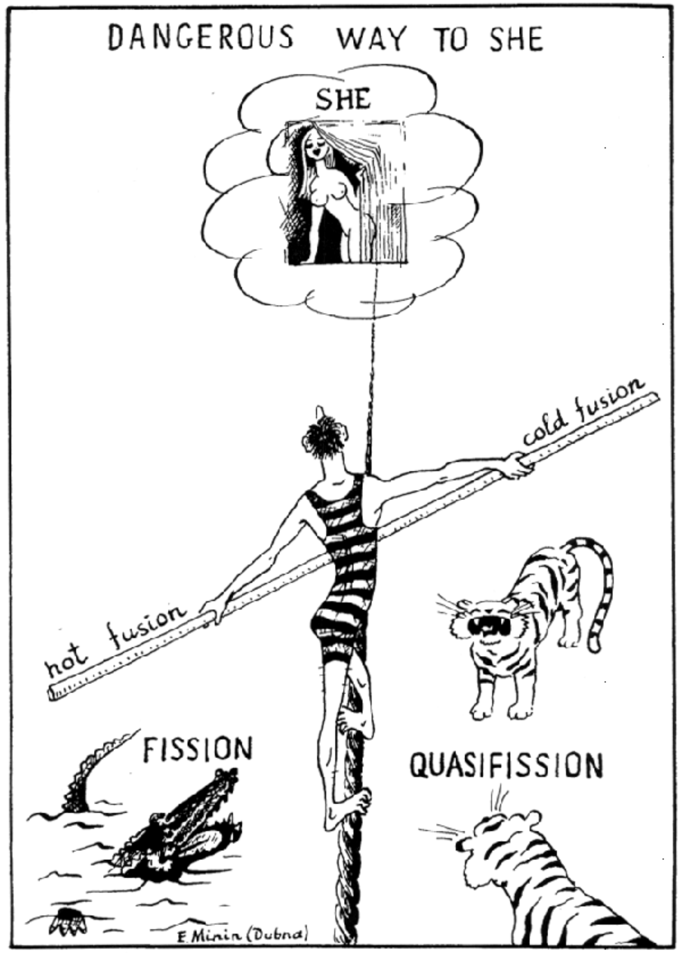


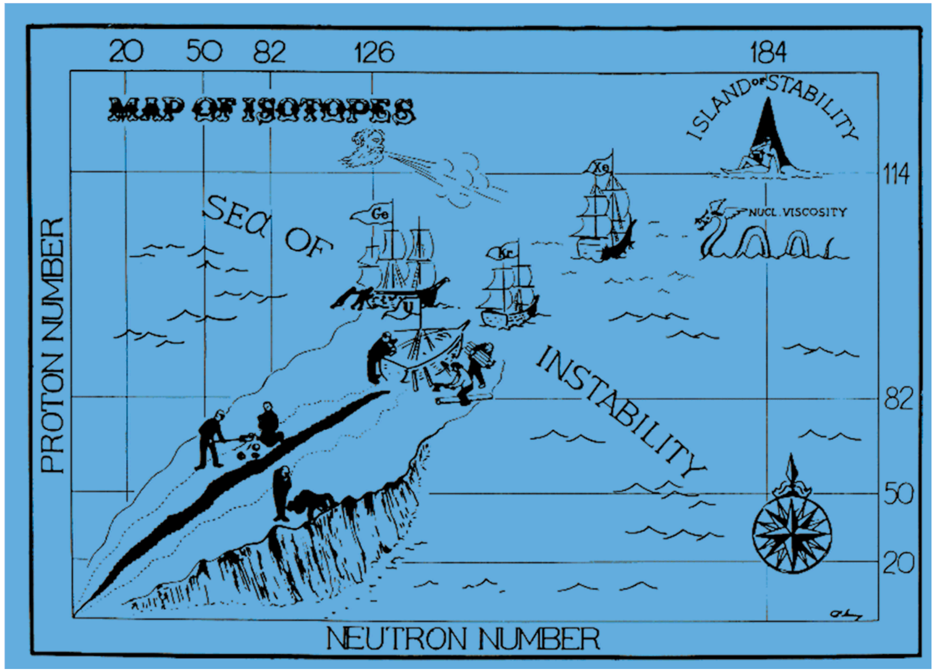
Fig. 8. Shell effect in the spontaneous-fission half-life T_{sf}.

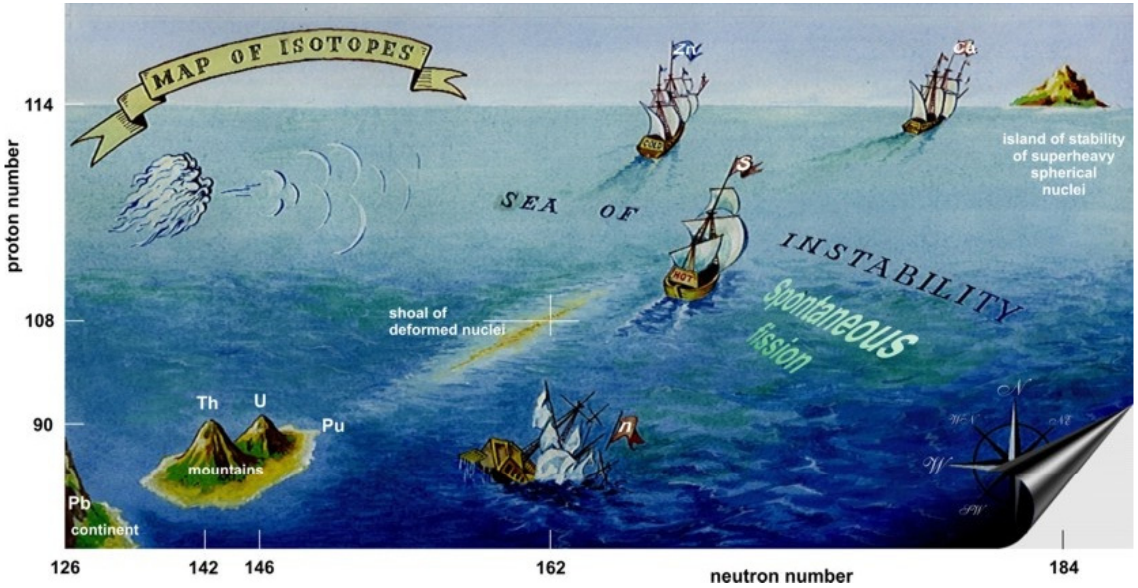
Map of the Nuclear Landscape



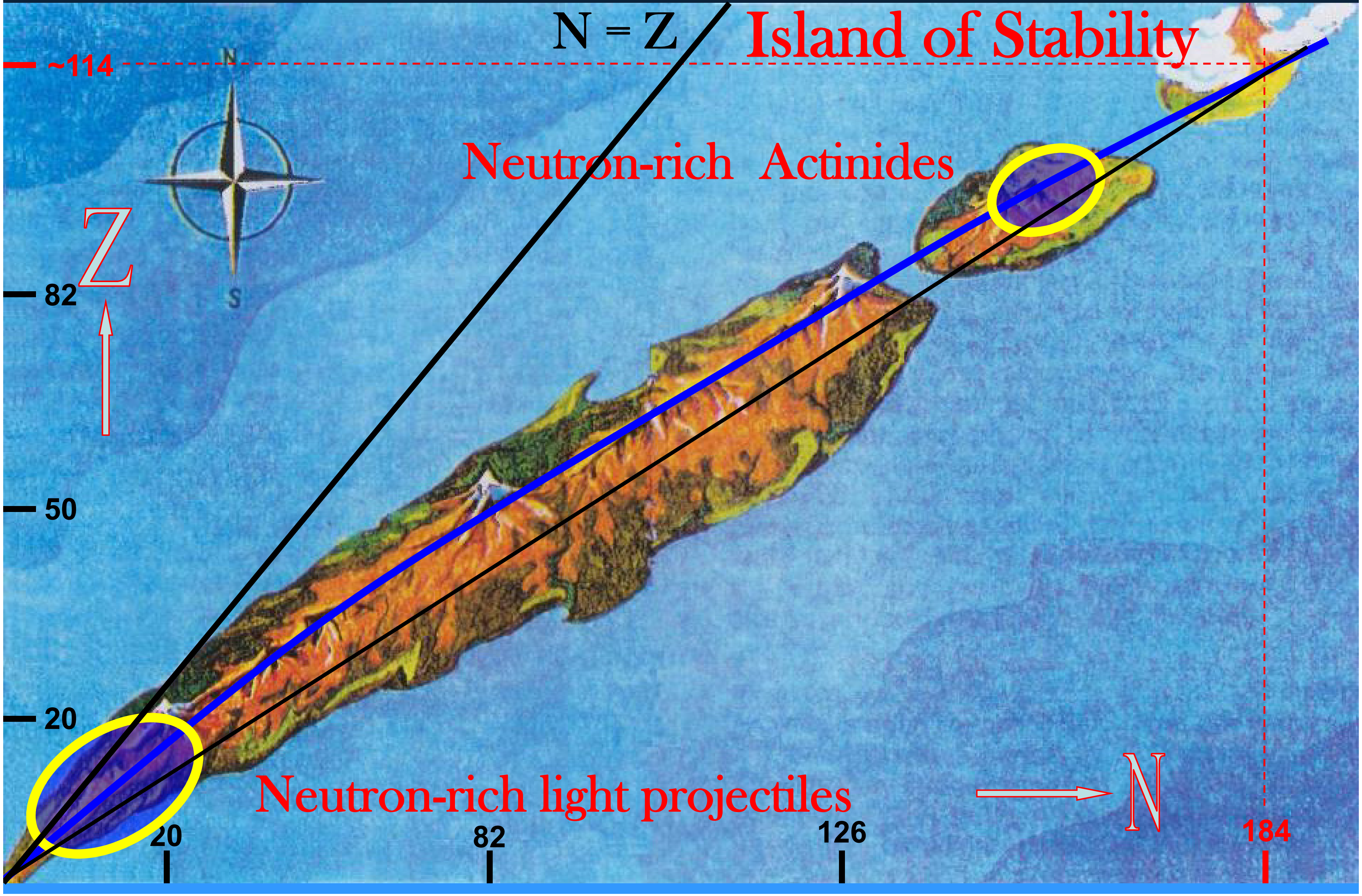
The quest for "SuperHeavy Elements" (SHE)



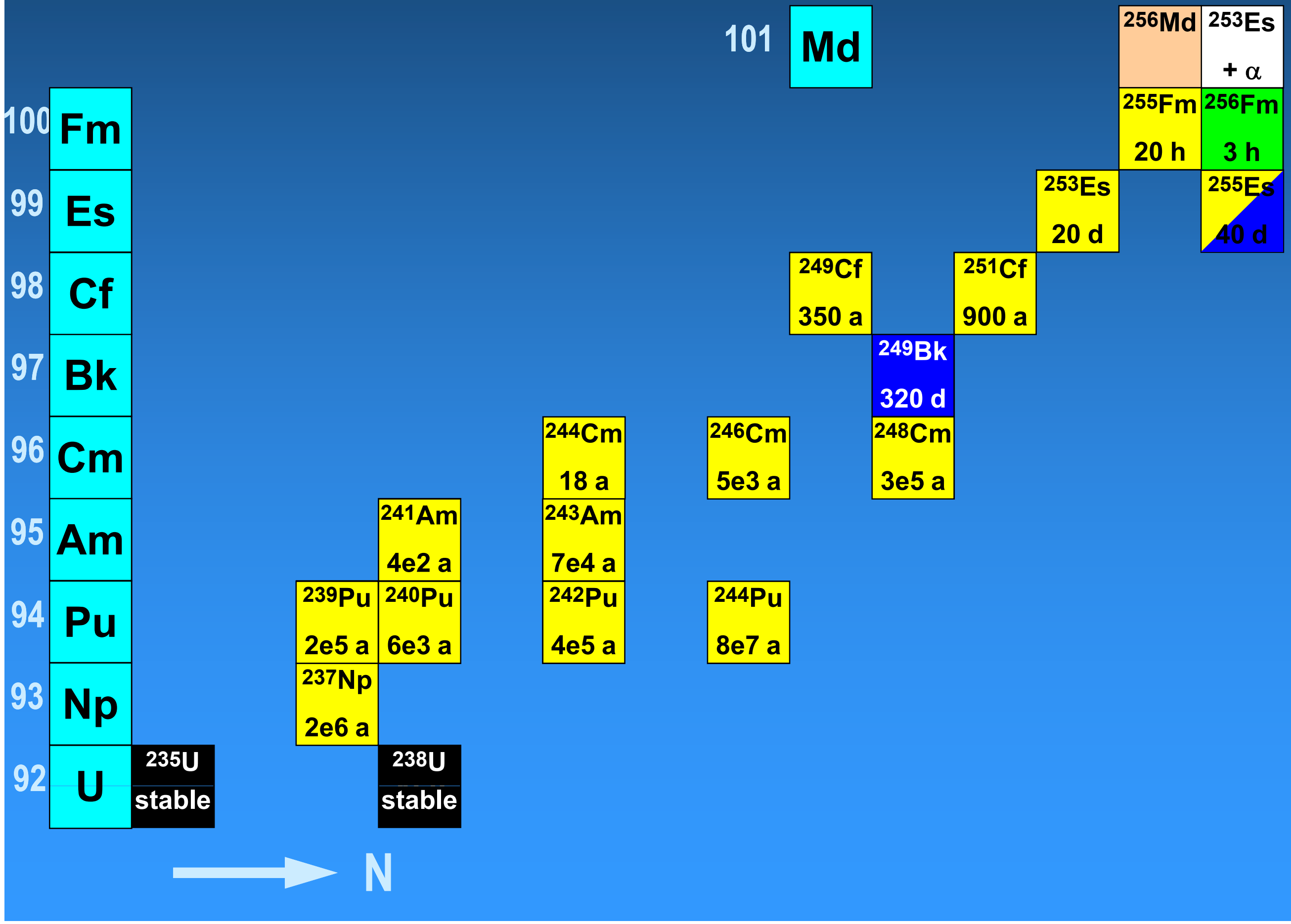




Map of the Nuclear Landscape



Md: Es target: 1e9 atoms
First "single atom chemistry"



101 Md

256Md | 253Es + α

100 Fm | 255Fm 20 h | 256Fm 3 h

99 Es | 253Es 20 d | 255Es 40 d

98 Cf | 249Cf 350 a | 251Cf 900 a

97 Bk | 249Bk 320 d

96 Cm | 244Cm 18 a | 246Cm 5e3 a | 248Cm 3e5 a

95 Am | 241Am 4e2 a | 243Am 7e4 a

94 Pu | 239Pu 2e5 a | 240Pu 6e3 a | 242Pu 4e5 a | 244Pu 8e7 a

93 Np | 237Np 2e6 a

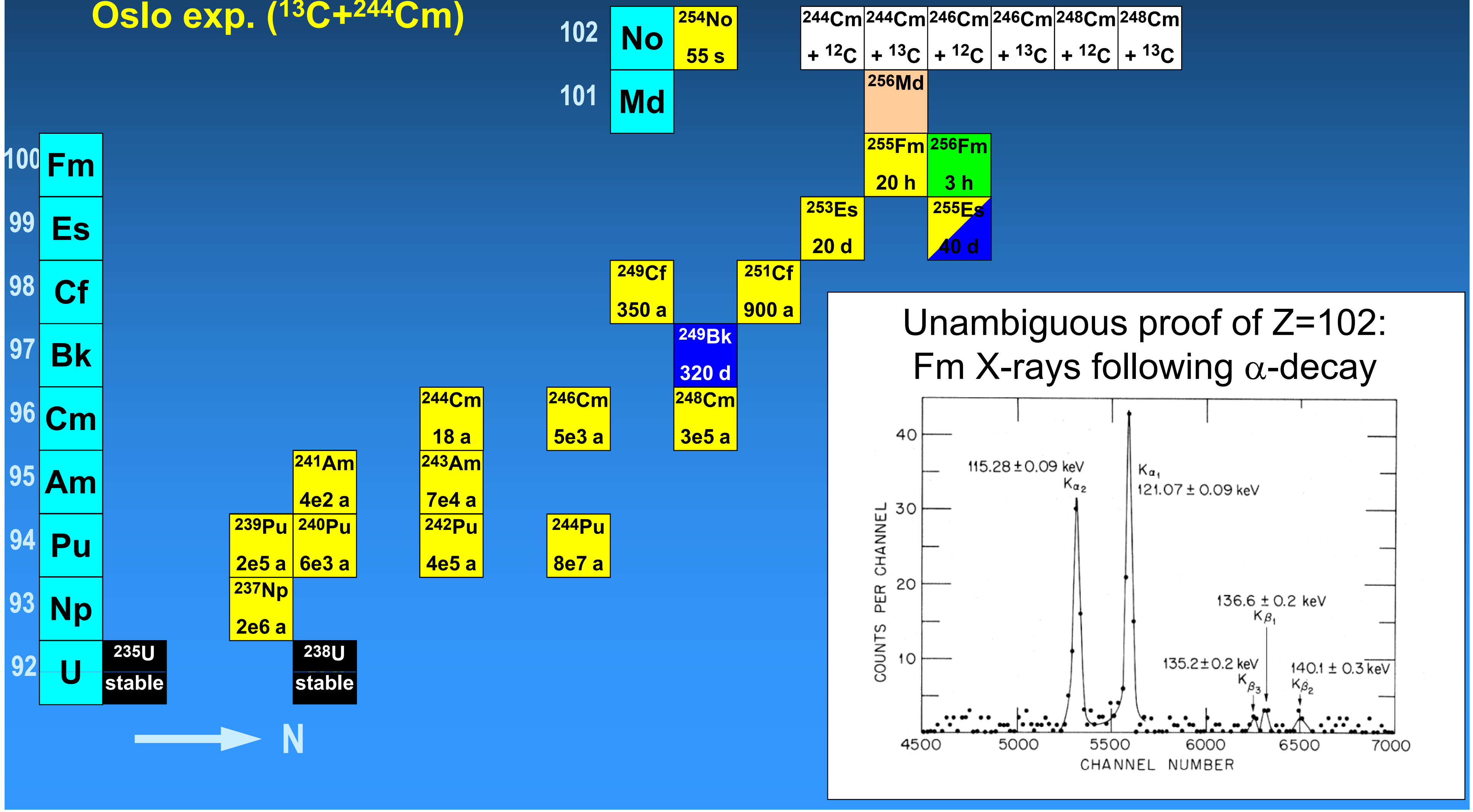
92 U | 235U stable | 238U stable

N

Md: Es target: 1e9 atoms
First "single atom chemistry"

102+: only with A>4 beams:
"Heavy Ion Beams"

No: Name from disproven
Oslo exp. ($^{13}C+^{244}Cm$)



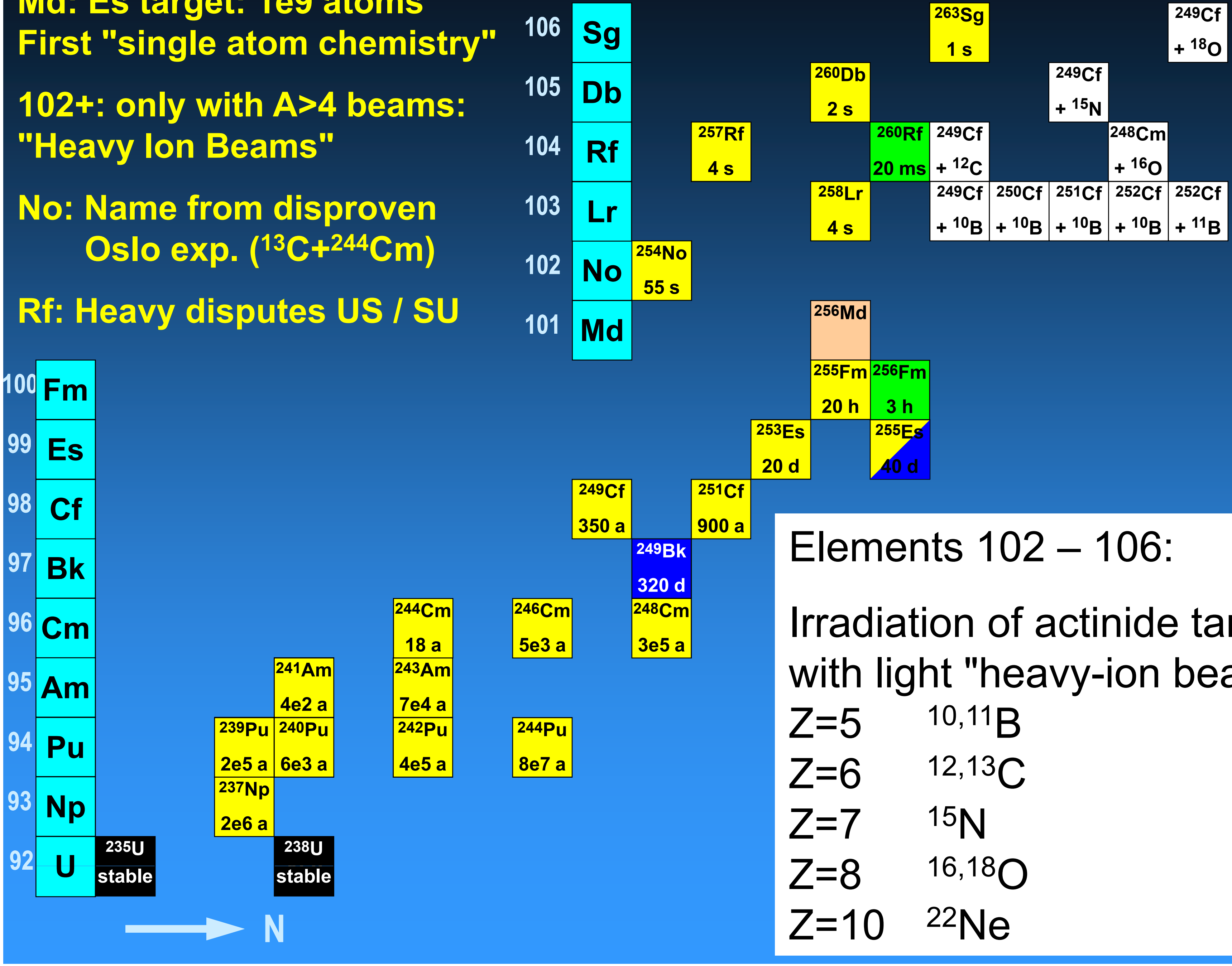
Unambiguous proof of Z=102:
Fm X-rays following α-decay

Md: Es target: 1e9 atoms
First "single atom chemistry"

102+: only with A>4 beams:
"Heavy Ion Beams"

No: Name from disproven
Oslo exp. (^{13}C+^{244}Cm)

Rf: Heavy disputes US / SU



Elements 102 – 106:

Irradiation of actinide targets with light "heavy-ion beams":

Z=5	^{10,11}B
Z=6	^{12,13}C
Z=7	^{15}N
Z=8	^{16,18}O
Z=10	^{22}Ne

FLNR/GSI: Cold fusion

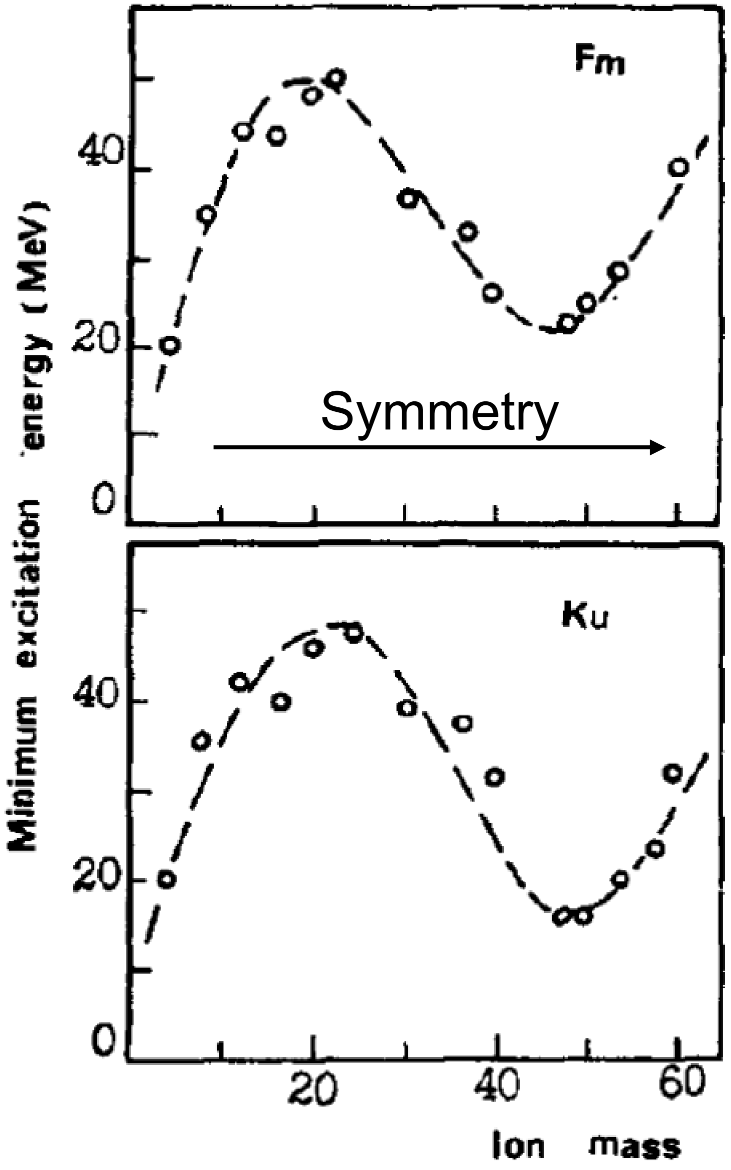
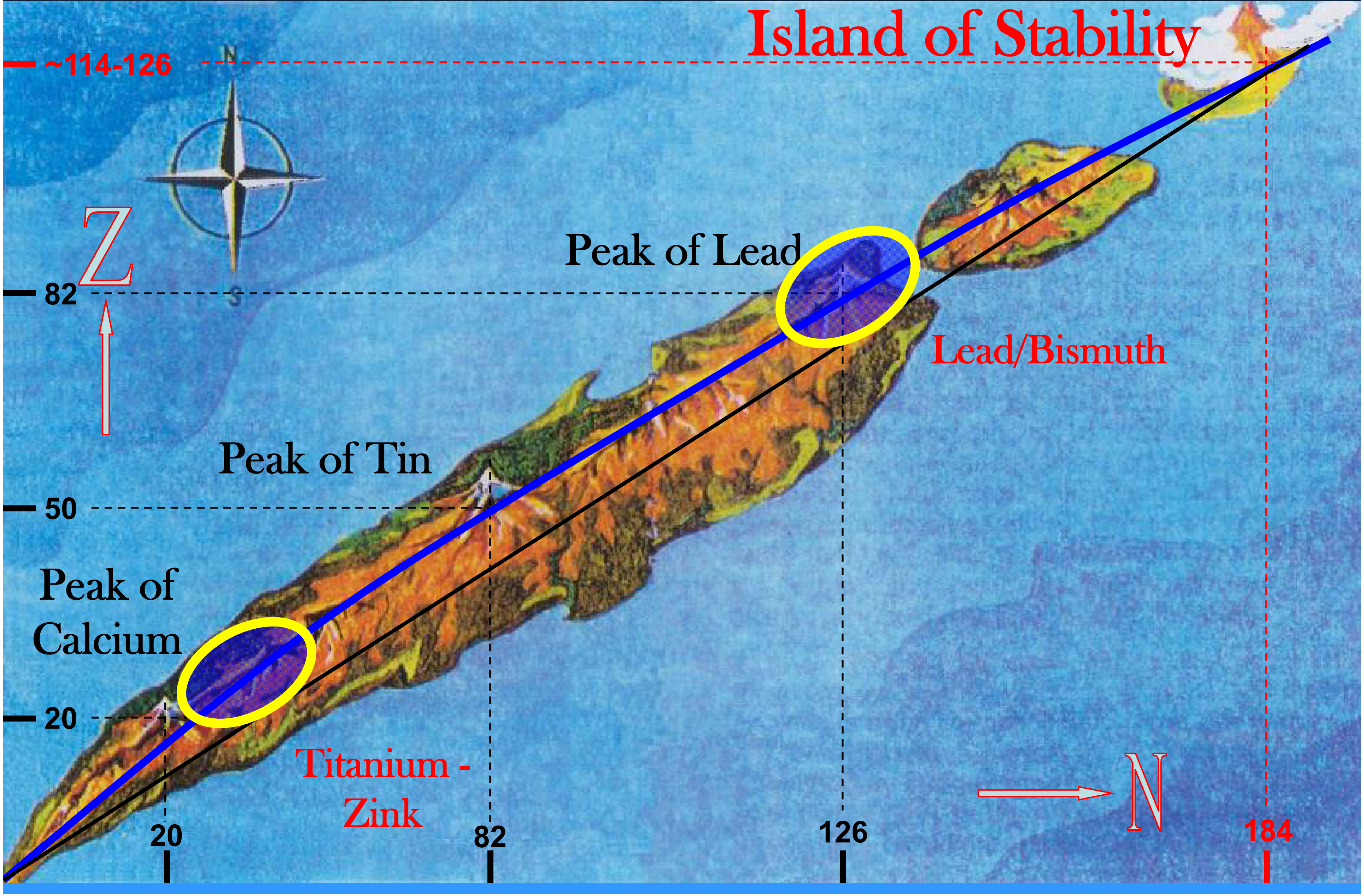


Fig. 5. Minimum excitation energy of the compound nuclei ^{248}Fm and ^{258}Ku formed in different target-projectile combinations. The dashed curves are drawn through the calculated E^*_{min} values shown by points.

Shell effects around ^{208}Pb
decrease excitation energy in CN
→ evaporation of fewer neutrons
→ loss in exit channel smaller
→ should enhance cross sections

^{207}Pb(^{40}Ar,3n)^{244}Fm
^{208}Pb(^{48}Ca,2n)^{254}No
→ high cross sections measured at FLNR!

Map of the Nuclear Landscape

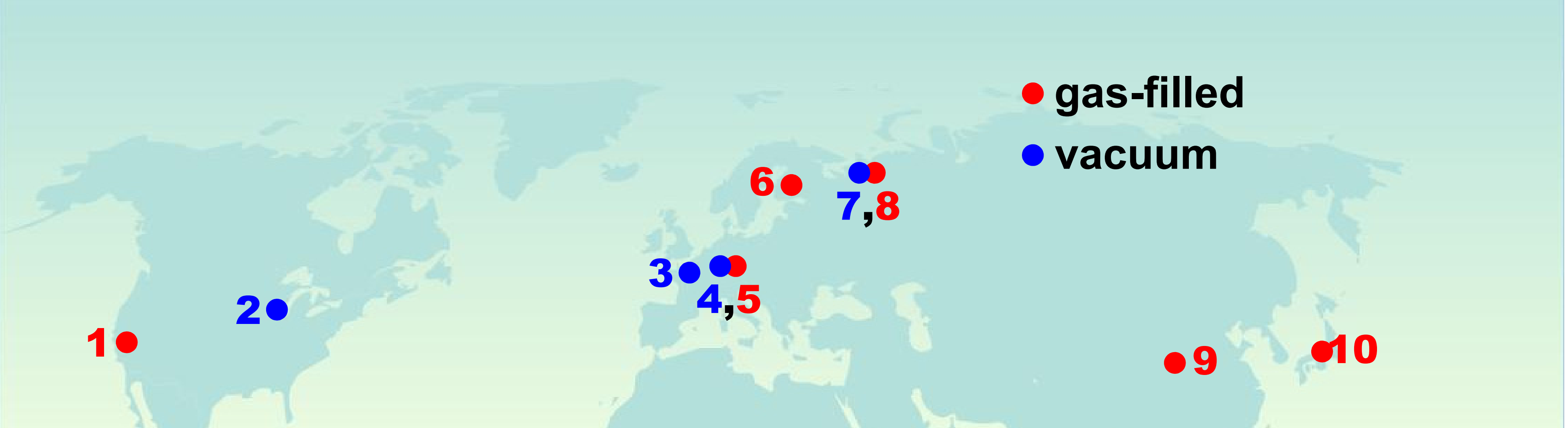


Experimental Techniques

Introduction to GSI

Physics experiments at recoil separators

SHE Separators world-wide



1: Berkeley Gas-filled Separator (BGS), LBNL, Berkeley (USA)

2: Fragment Mass Analyzer (FMA), ANL, Argonne (USA)

3: Ligne d'Ions Super Epluchés (LISE III), GANIL, Caen (F)

4: Separator for Heavy Ion Products (SHIP), GSI, Darmstadt (D)

5: TransActinide Separator and Chemistry Apparatus (TASCA), GSI

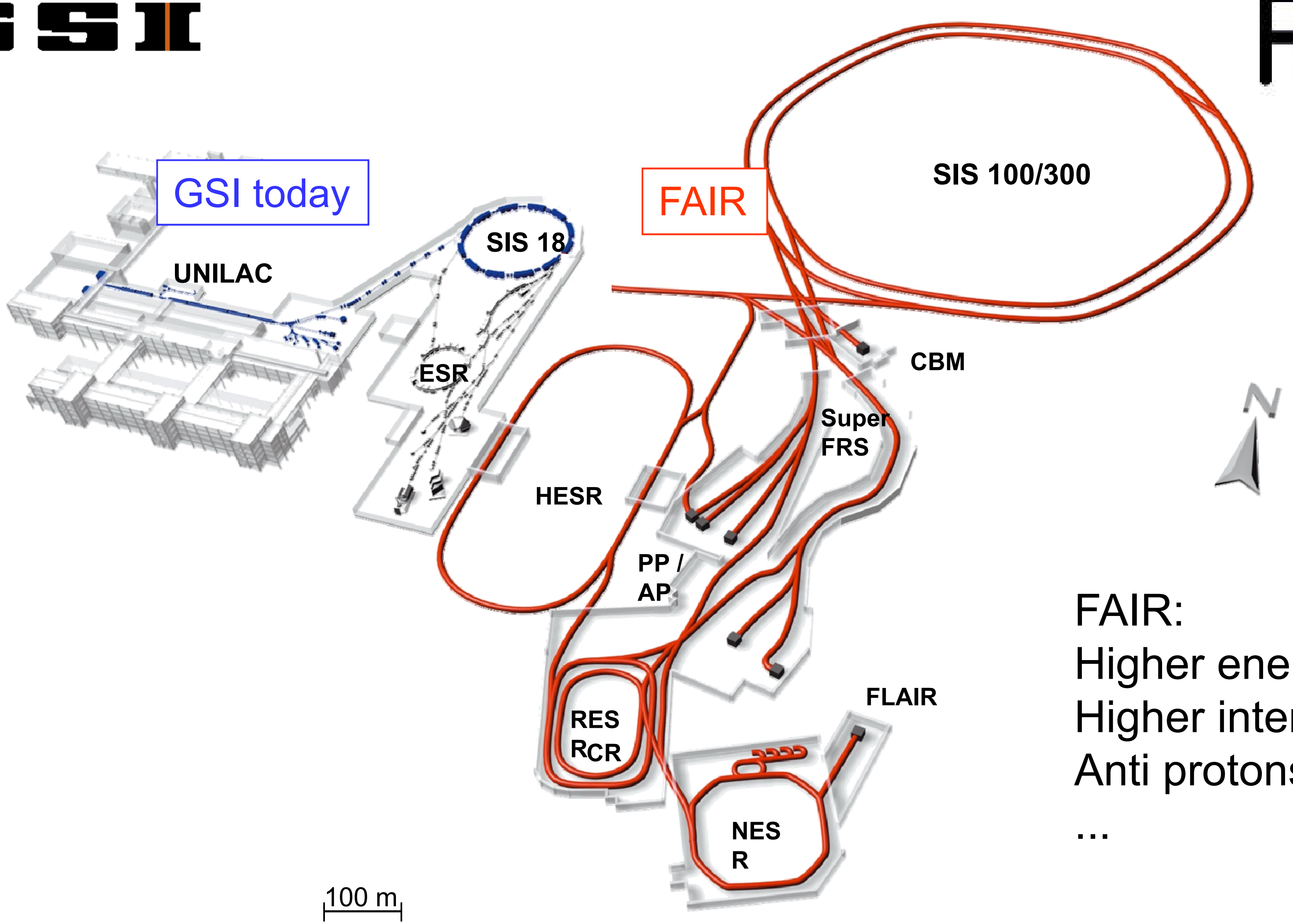
6: Recoil Ion Transport Unit (RITU), JYFL, Jyväskylä (SF)

7: Dubna Gas-Filled Recoil Separator (DGFRS), FLNR, Dubna (RU)

8: VASSILISSA, FLNR, Dubna (RU)

9: Gas-filled recoil separator at Lanzhou, IMP, Lanzhou (PRC)

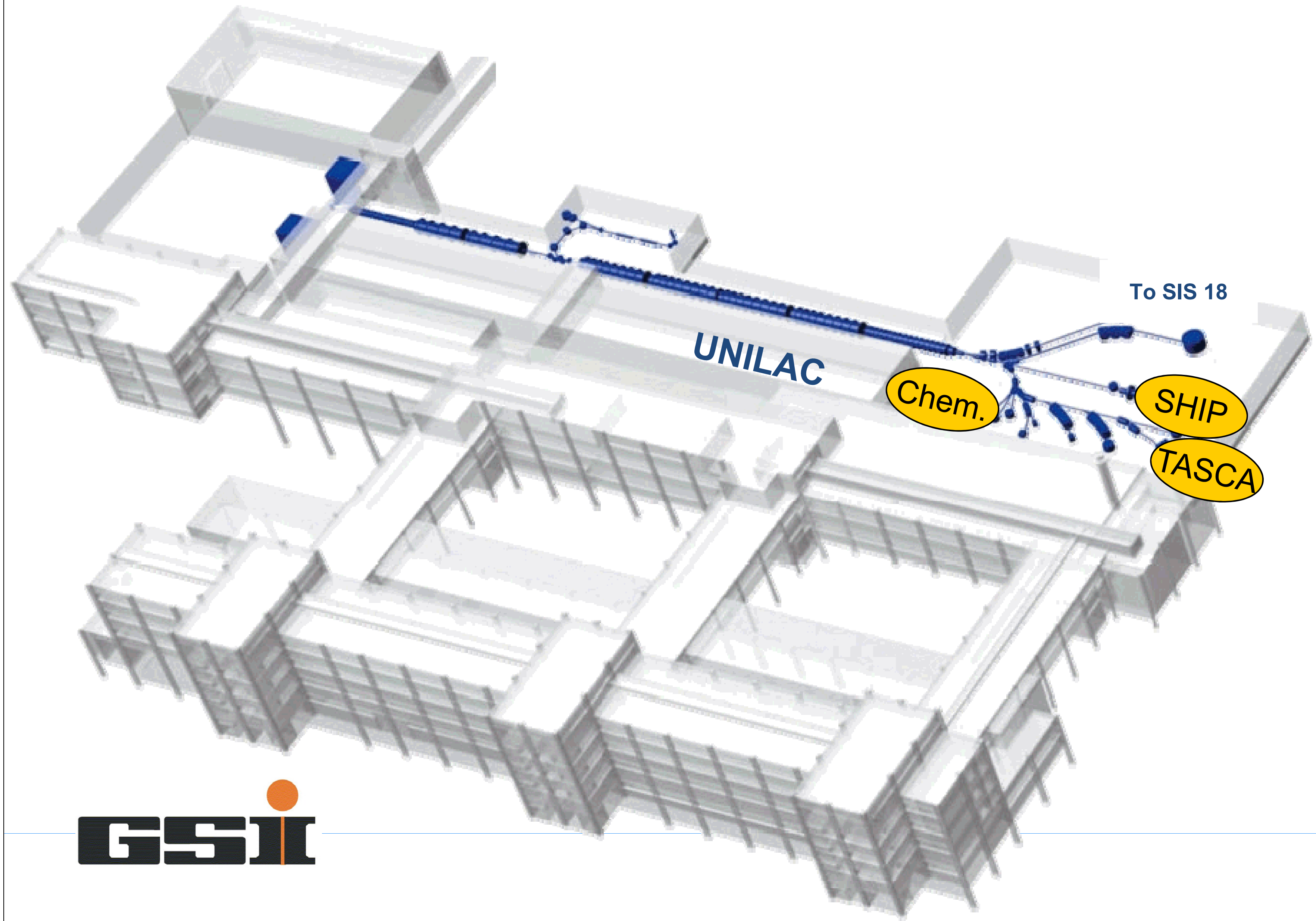
10: GAs-filled Recoil Ion Separator (GARIS/GARIS II), RIKEN, Wako (J)



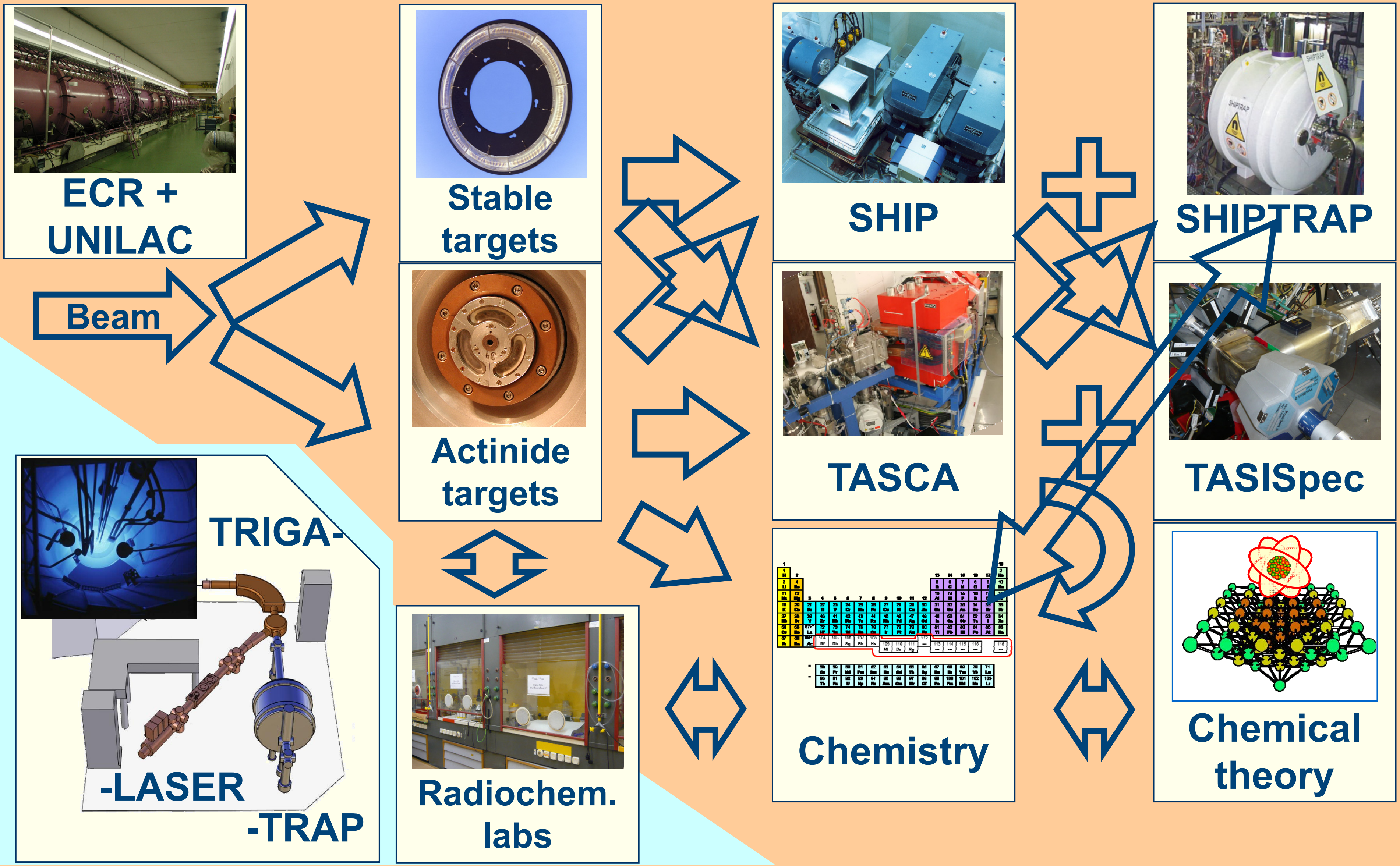
FAIR:
Higher energy
Higher intensity
Anti protons
...

GSI Helmholtzzentrum für Schwerionenforschung mbH
Facility for Antiproton and Ion Research

SHE Research at GSI



Unique Combination for SHE S



ECR + UNILAC

Beam

TRIGA-

-LASER

-TRAP

Stable targets

Actinide targets

Radiochem. labs

SHIP

TASCA

Chemistry

SHIPTRAP

TASISpec

Chemical theory

Separation in E and M Dipol

Different ionic species are spatially separated by exploiting their different response (=radius of curvature) to the Lorentz force:

$$\vec{F} = q \cdot \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

Separators are built such that all vectors are orthogonal (or radial, in case of the E dipole). Then equating with the centrifugal force yields the respective rigidities:

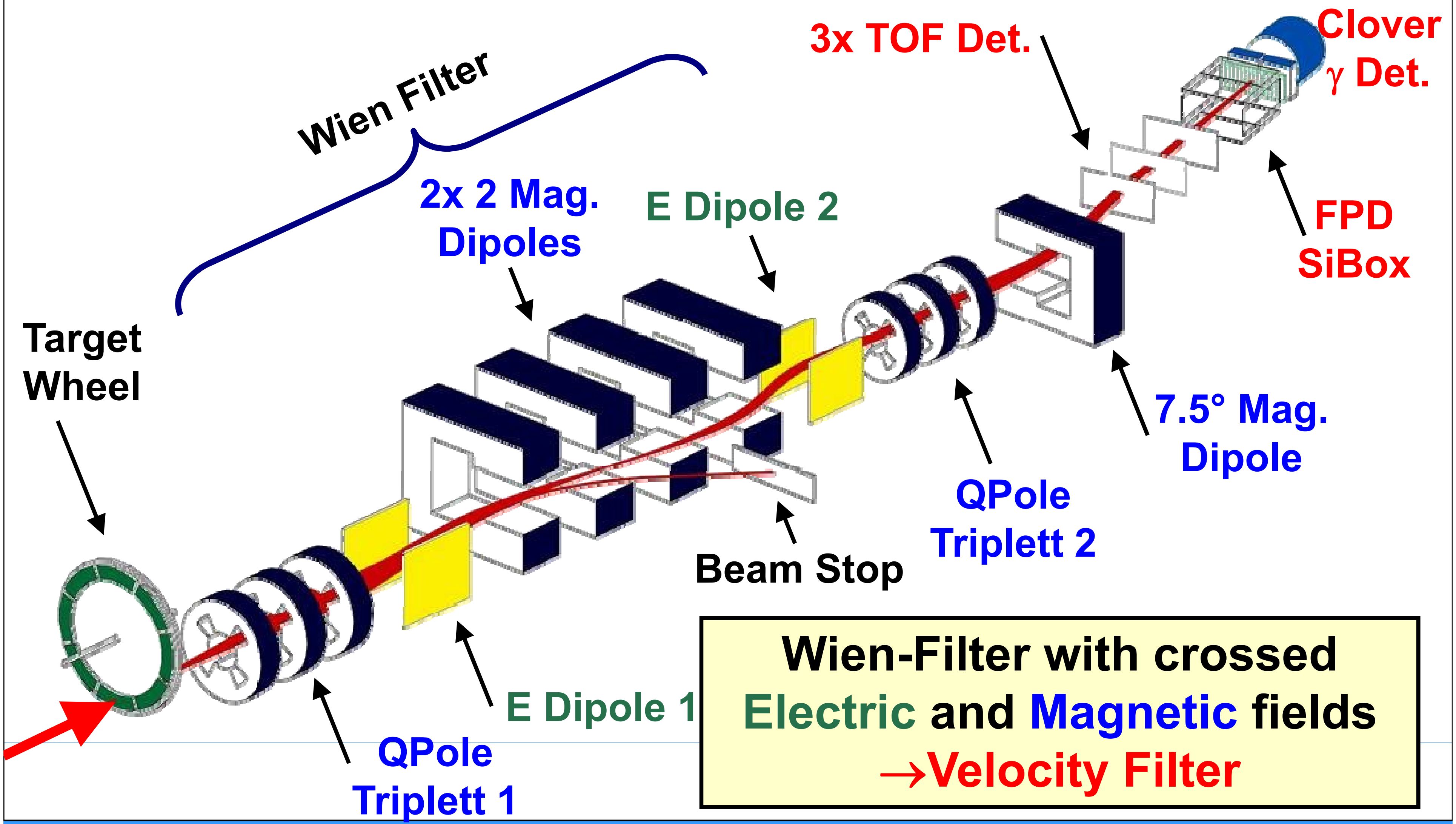
Electric dipole: $E \cdot \rho\,[\mathrm{MV}] = \frac{m \cdot v^2}{q}$

Magnetic dipole: $B \cdot \rho\,[\mathrm{T \cdot m}] = \frac{m \cdot v}{q}$

Magnetic quadrupole multiplets as ion-optical lenses for focusing

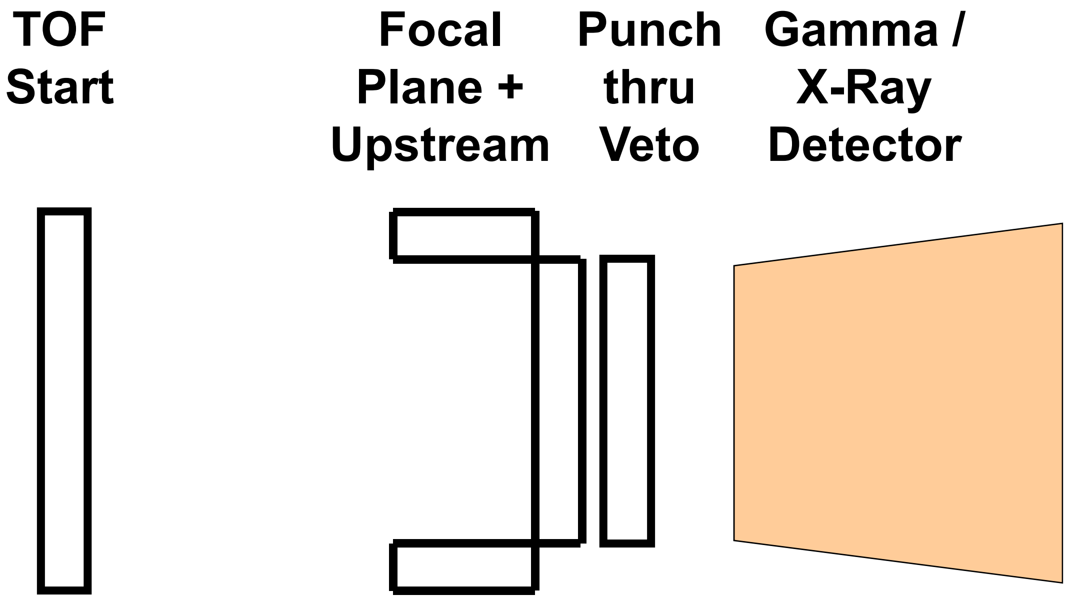
Separation in Vacuum

Separator for Heavy Ion reaction Products – SHIP



Wien-Filter with crossed
Electric and Magnetic fields
→Velocity Filter

Generic Recoil Separator Detection System



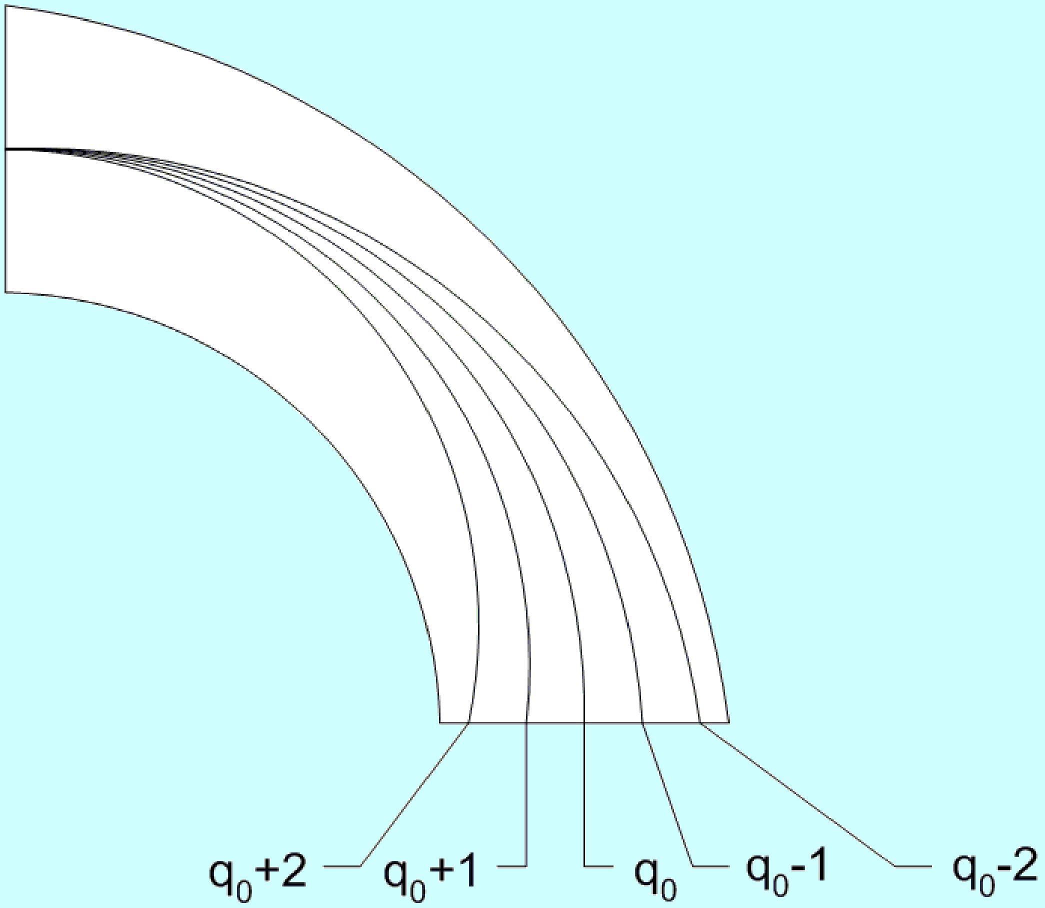
FPD Registers:

α-particles

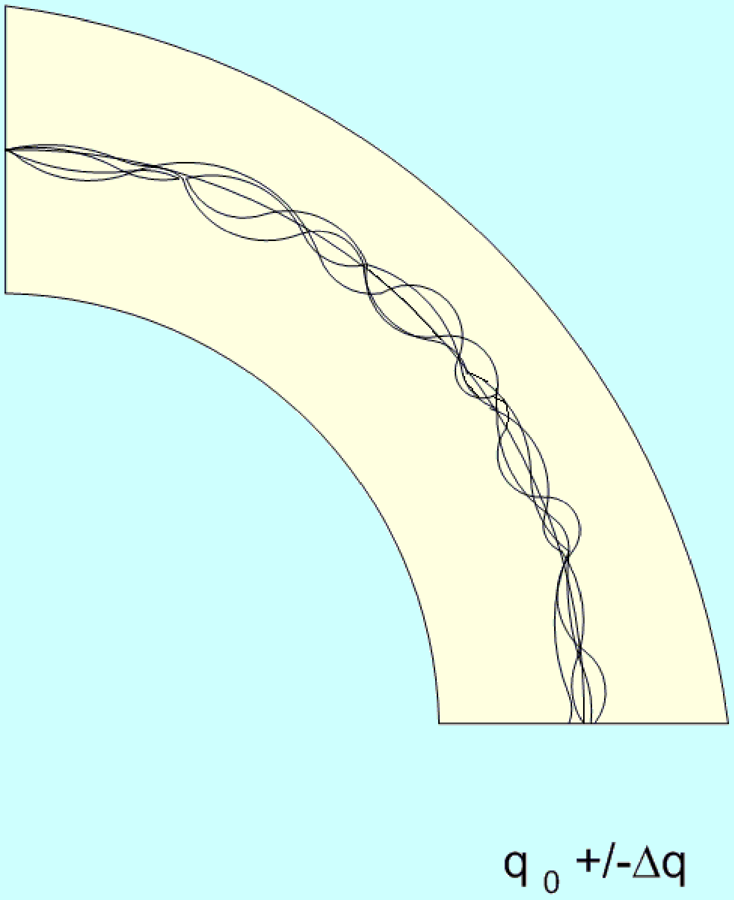
Conversion Electrons

Separation in gas-filled dipoles

In vacuum



In dilute gas



GSI JOHANNES GUTENBERG UNIVERSITÄT MAINZ TUM LUND UNIVERSITY BERKELEY LAB LMU HELMHOLTZ ASSOCIATION Helmholtz Institute Mainz PAUL SCHERRER INSTITUT PSI ...

TASCA

www.gsi.de/tasca

GSI

TASCA

Target Chamber
side view

www.gsi.de/tasca

TASCA

Target Chamber
side view

www.gsi.de/tasca

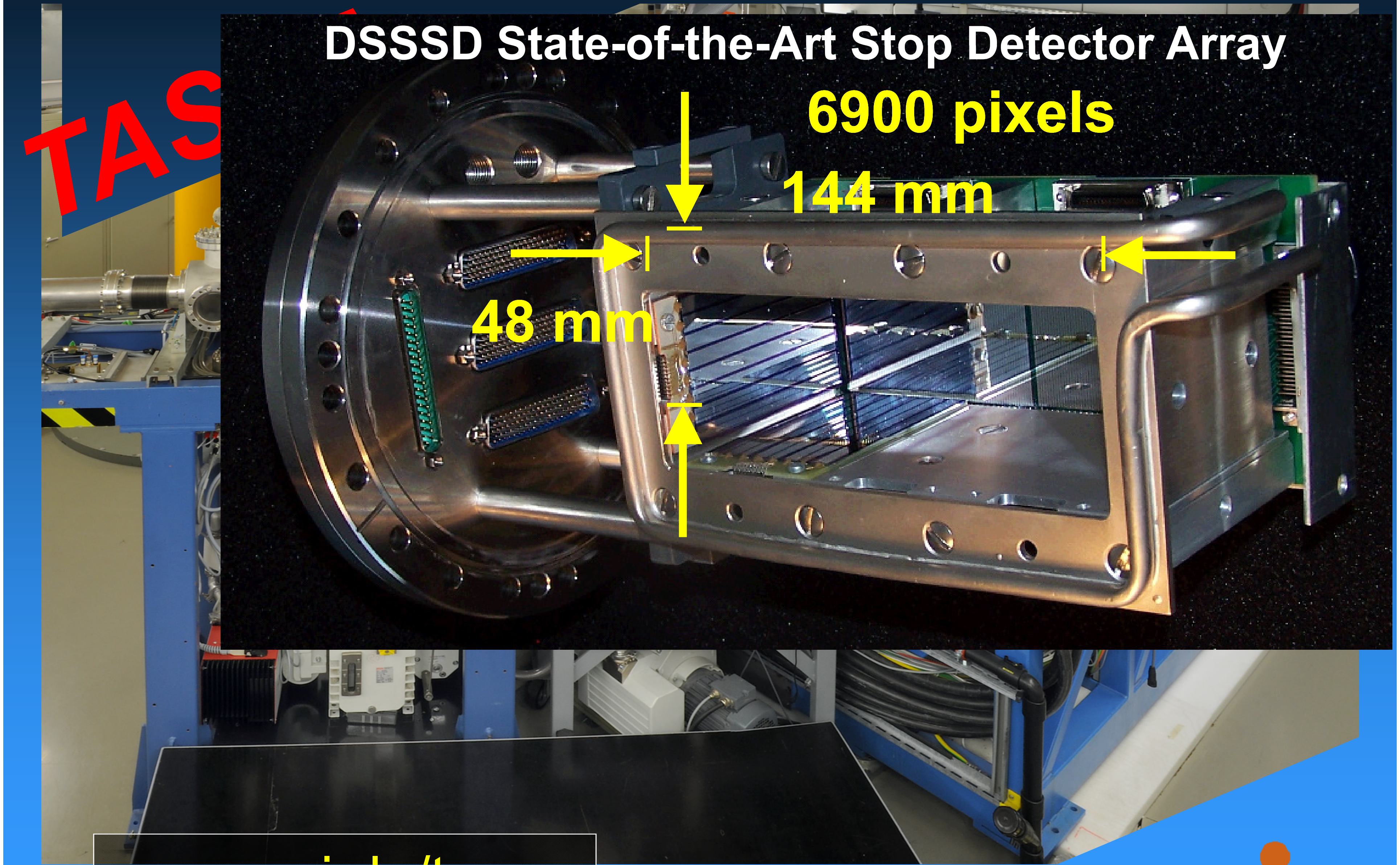
TASCA

DQQ-configuration

$B\rho_{max} \approx 2.4$ Tm

www.gsi.de/tasca

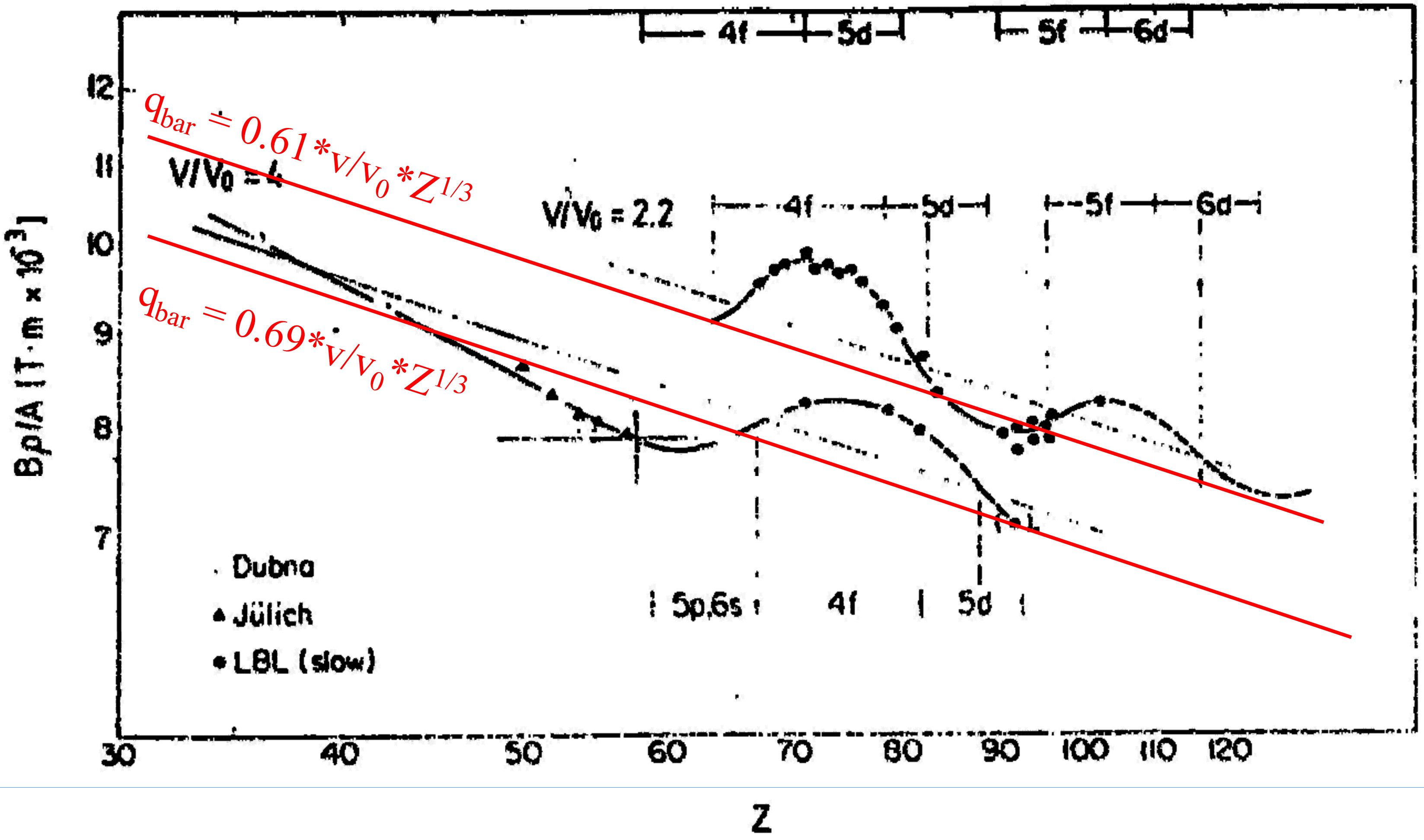
DSSSD State-of-the-Art Stop Detector Array



www.gsi.de/tasca

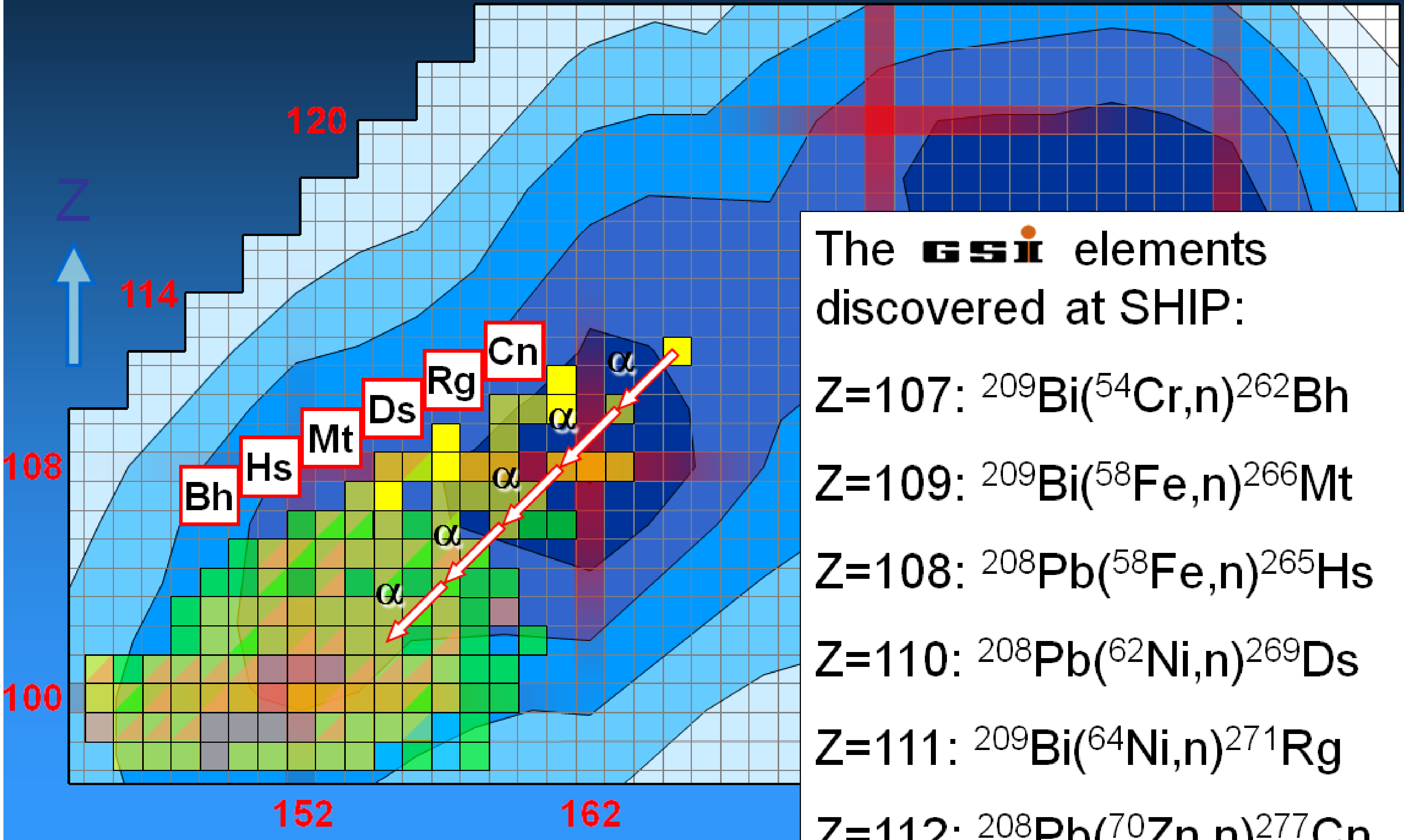
Average charge state in dilute He

$$B\rho\ [\mathrm{T\cdot m}] = m\cdot v/q \approx 0.0227\cdot(v/v_0)\cdot A/q$$



Ghiorso et al., Nucl. Instrum. Meth. A 269, 192 (1988)

Superheavy elements on the mic-mac landscape of today



The GSI elements discovered at SHIP:

Z=107: ^{209}Bi(^{54}Cr,n)^{262}Bh

Z=109: ^{209}Bi(^{58}Fe,n)^{266}Mt

Z=108: ^{208}Pb(^{58}Fe,n)^{265}Hs

Z=110: ^{208}Pb(^{62}Ni,n)^{269}Ds

Z=111: ^{209}Bi(^{64}Ni,n)^{271}Rg

Z=112: ^{208}Pb(^{70}Zn,n)^{277}Cn

SHIP Excitation Functions with ^{208}Pb Targets

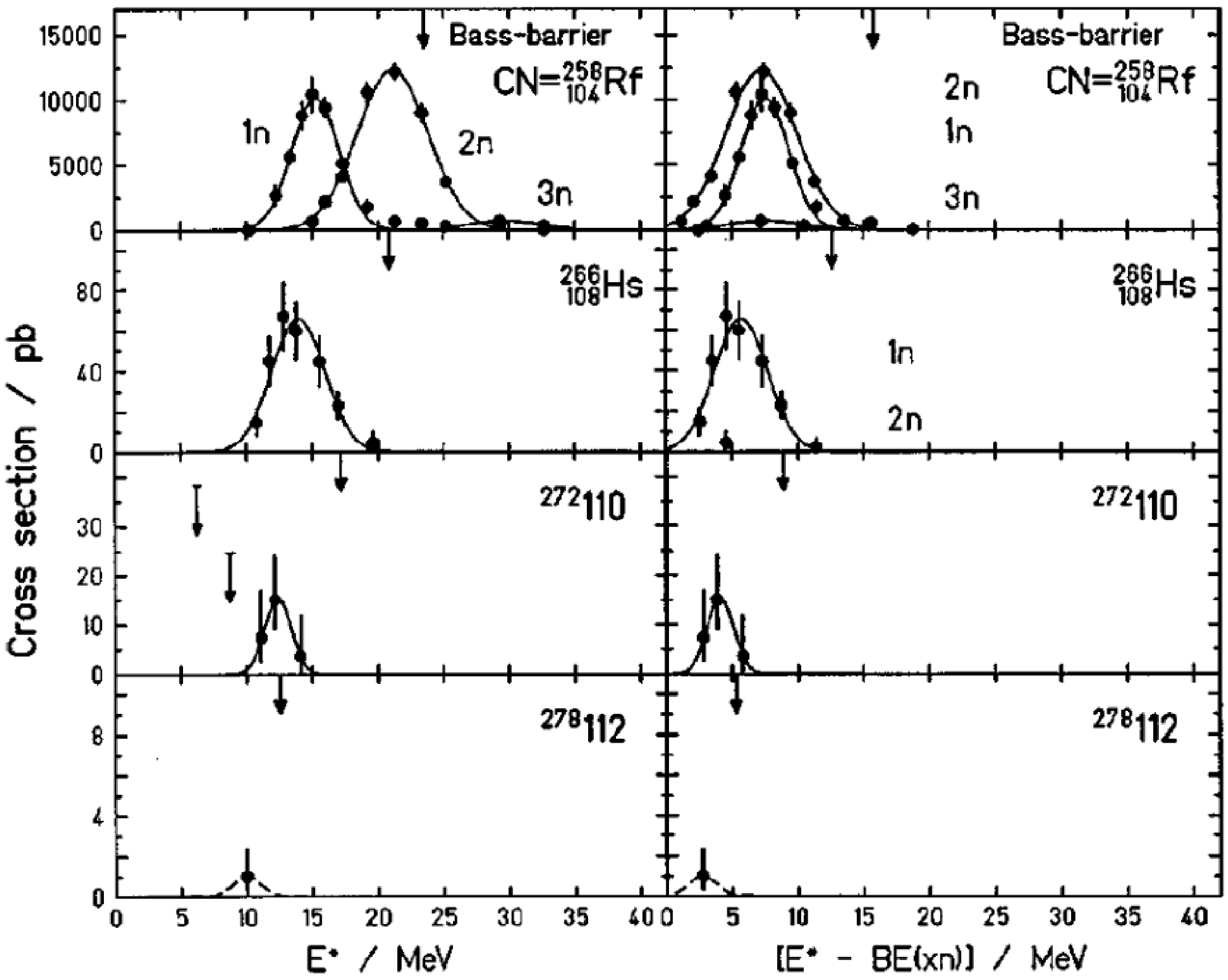
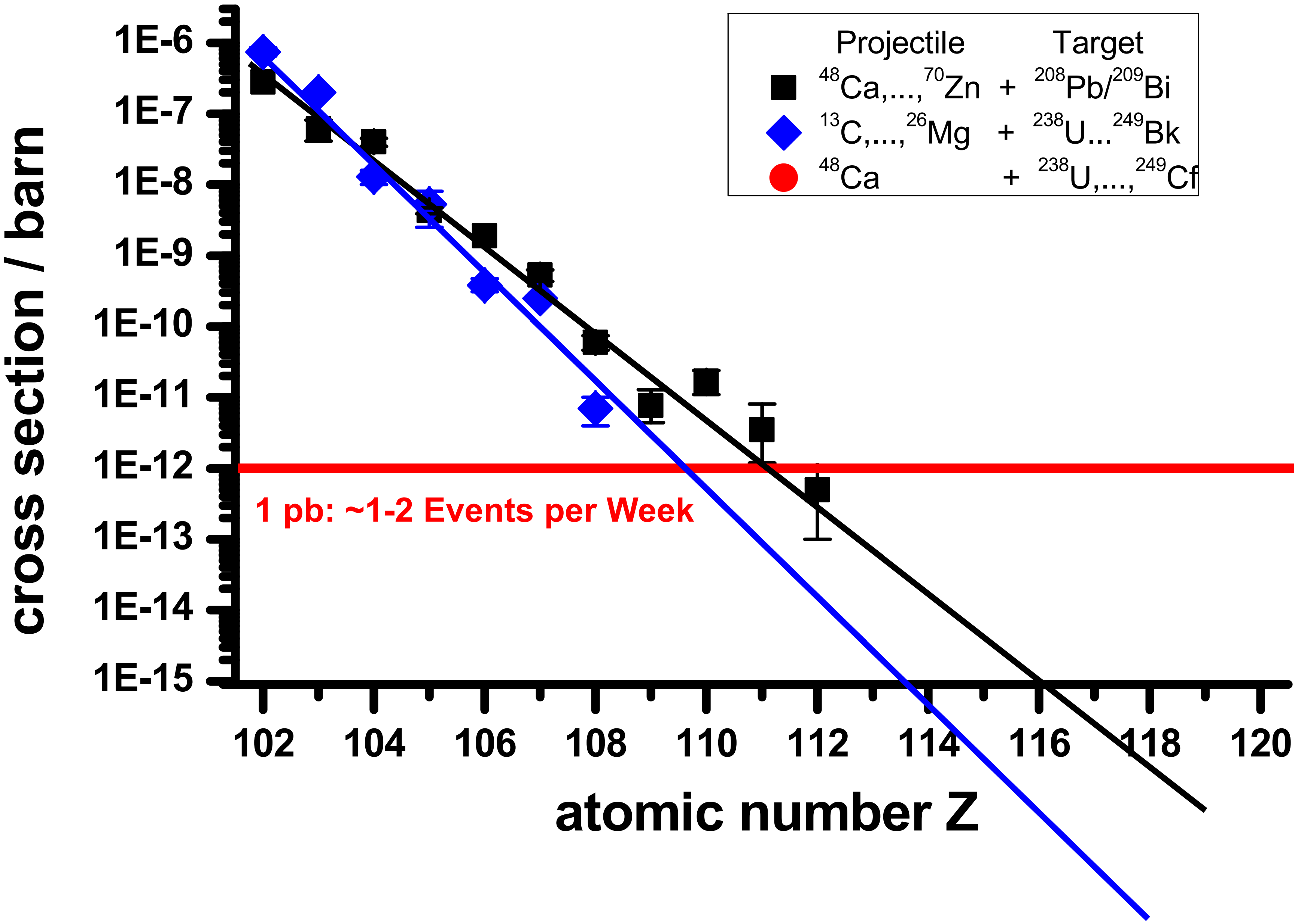


FIG. 18. Measured even-element excitation functions.

S. Hofmann et al.

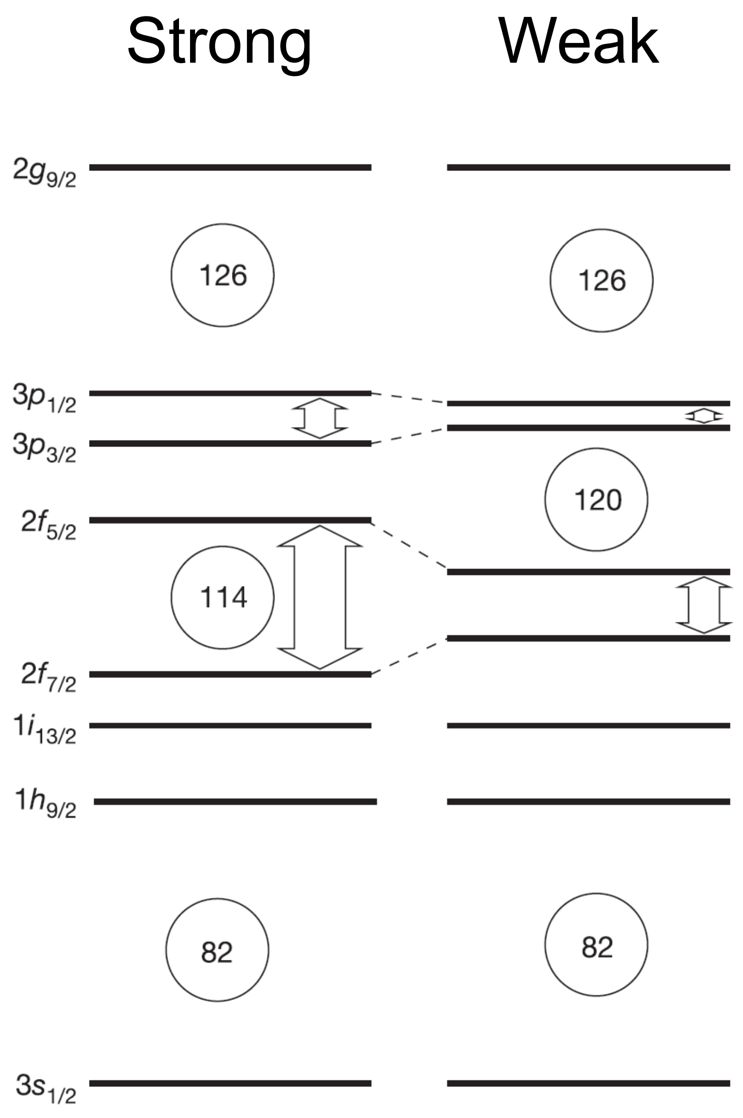
Cross Sections in Hot / Cold / ^{48}Ca Induced Fusion Reactions



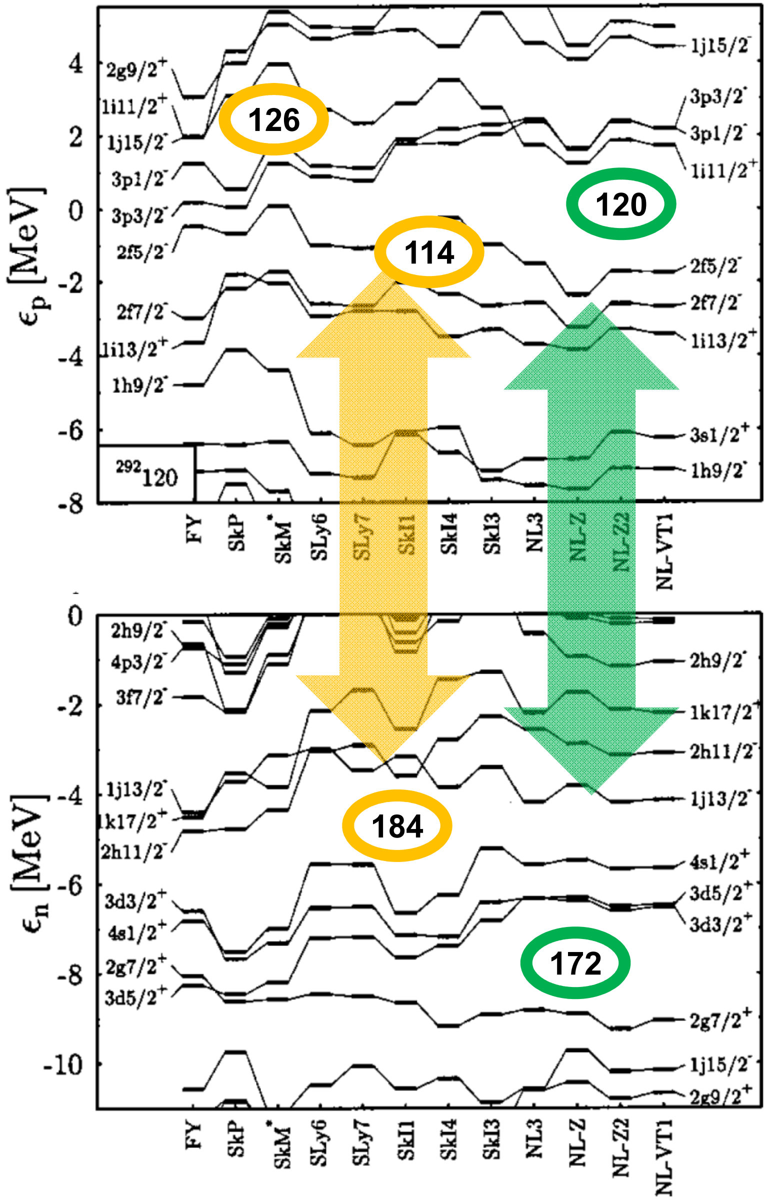
Question

Now where is the next magic number beyond Z=82?

Spin orbit splitting in superheavy nuclei

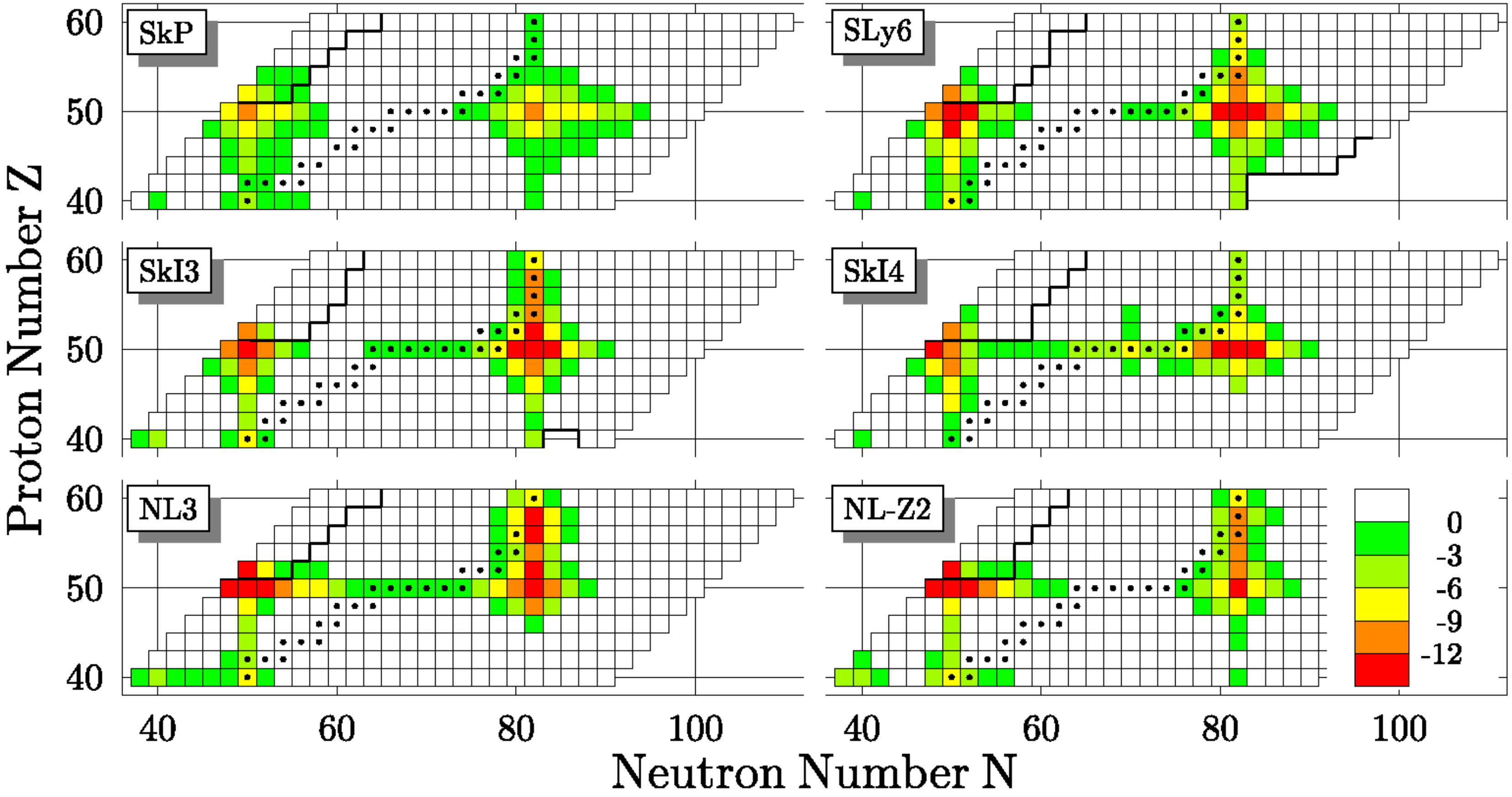


R.-D. Herzberg et al., Nature 442 (2006) 896



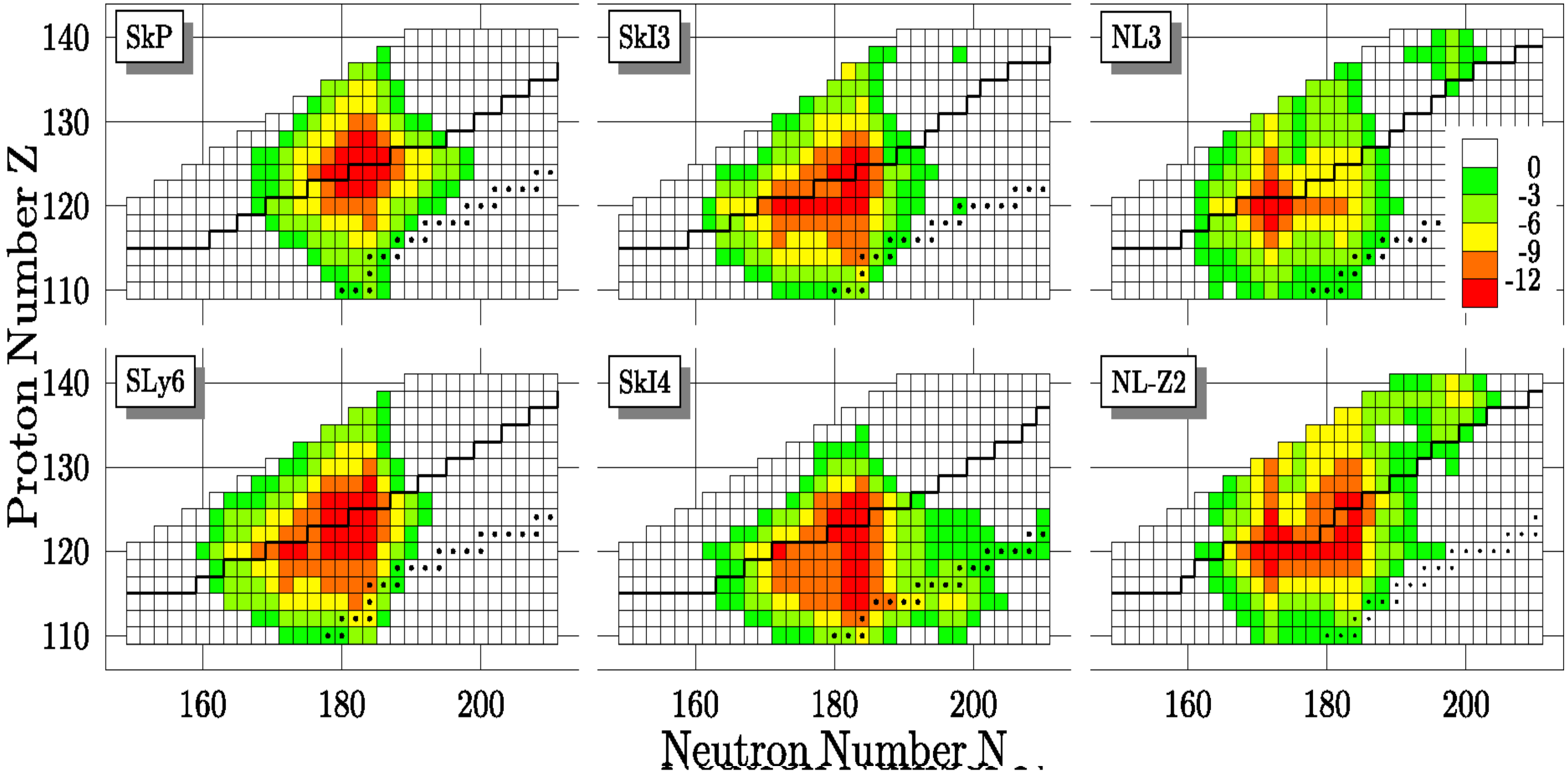
M. Bender et al., Phys. Rev. C 60 (1999) 034304

Nuclear shells



M. Bender et al., Phys. Lett. B 515 (2001) 42

Nuclear shells



M. Bender et al., Phys. Lett. B 515 (2001) 42