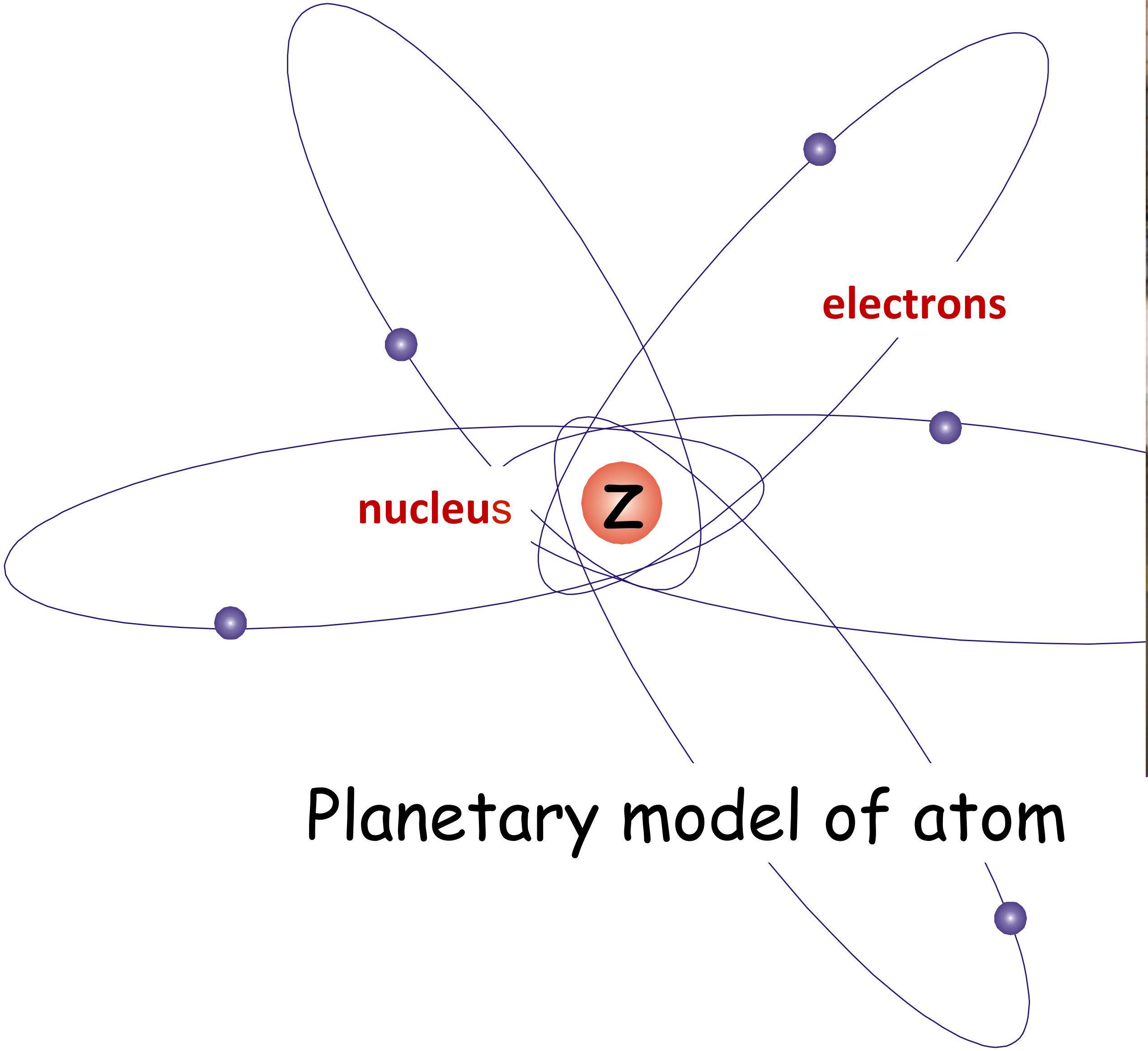
SUPER HEAVY NUCLEI

Yuri Oganessian

TIAS (TAMU) and FLNR(JINR)

Cyclotron Institute of the TAMU
July 21, 2015, Texas, USA

Ernest Rutherford
March 7, 1911 Manchester



Planetary model of atom

We will discuss:

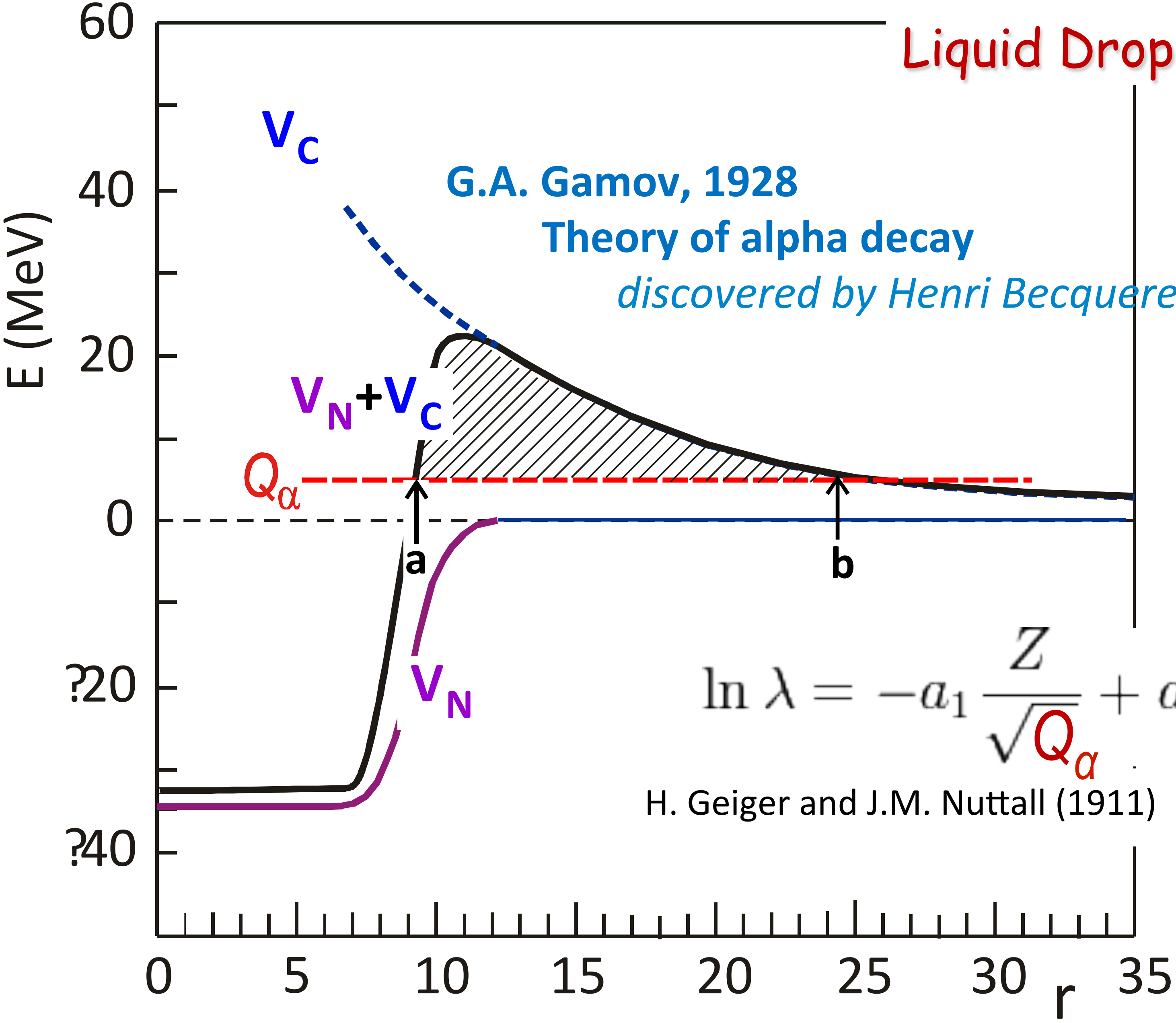
- How big a nucleus may be,
- What is a maximum number of protons and neutrons it may contain,
- What is the limit of atomic nuclei mass and how it is determined.

In the first attempts of describing the properties of nuclear matter (1928) a daring supposition was made that atomic nucleus is an object similar to a drop of positively charged liquid, the so called

Liquid-Drop Model of Nucleus

G. Gamow 1928

Liquid Drop Model



G.A. Gamov, 1928

Theory of alpha decay

discovered by Henri Becquerel, 1896

$$\ln \lambda = -a_1 \frac{Z}{\sqrt{Q_\alpha}} + a_2$$

H. Geiger and J.M. Nuttall (1911)

Semi-empirical mass formula (C.F. von Weizsäcker, 1932)

structure

$$E\,(A,Z) = a_1A - a_2A^{2/3} - a_3Z^2/A^{1/3} - a_4(A/2-Z)^2/A + a_5A^{-3/4}$$

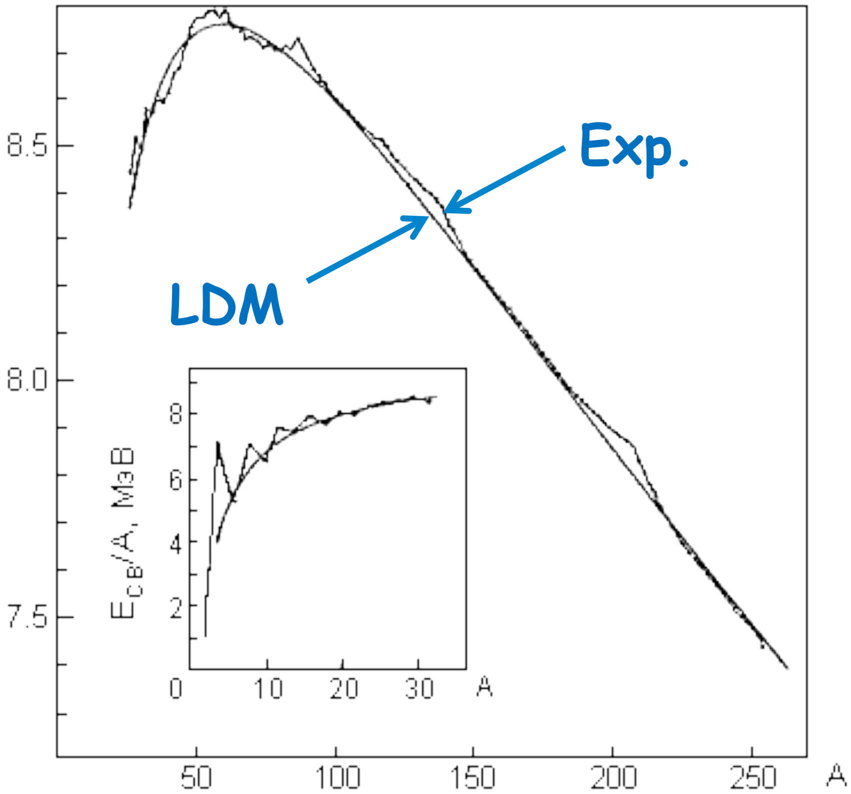
volume term

surface term

Coulomb Term

asymmetry term

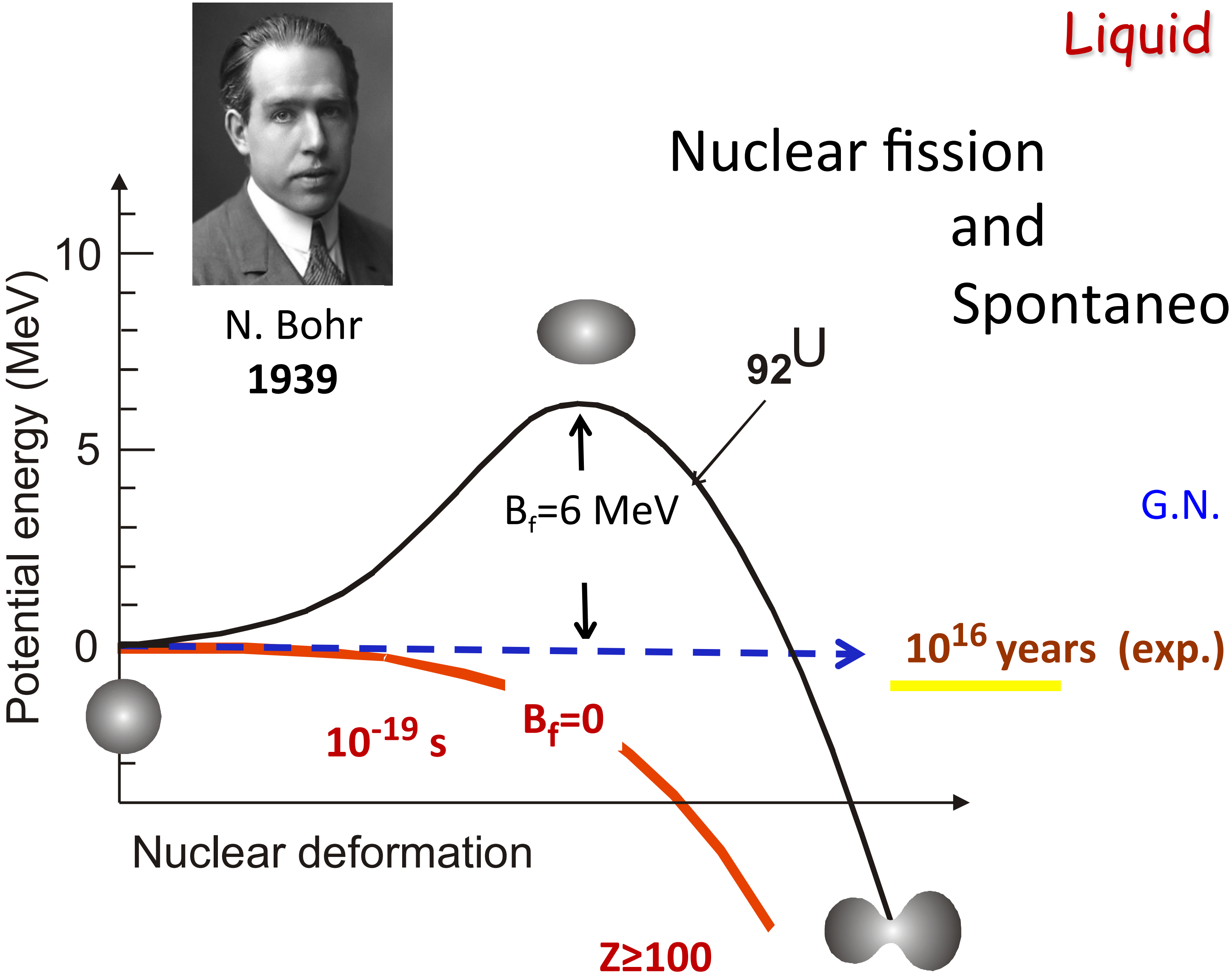
pairing term



Liquid Drop Model

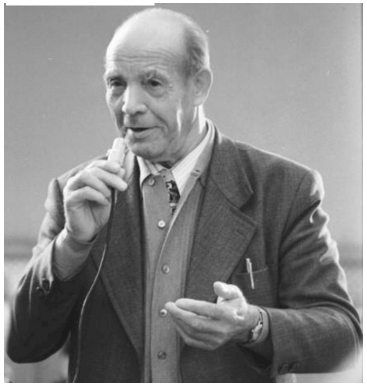
Liquid Drop Model

Nuclear fission
and
Spontaneous fission



G.N. Flerov

1940

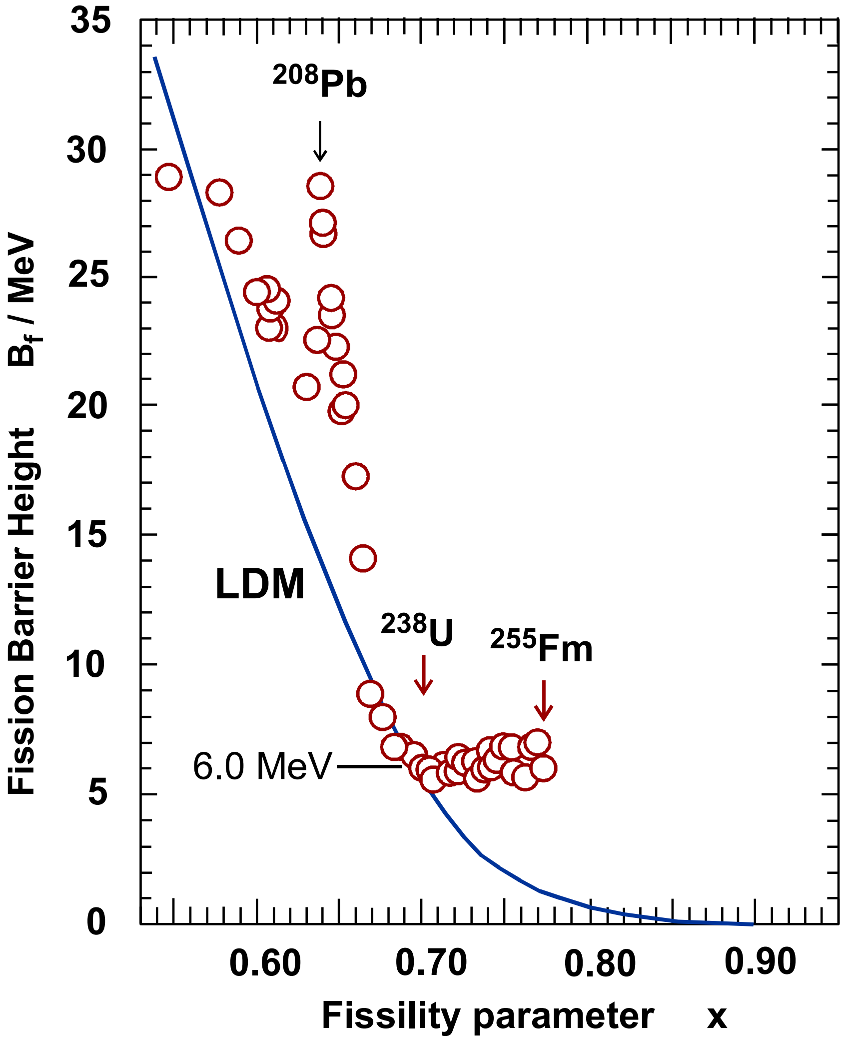


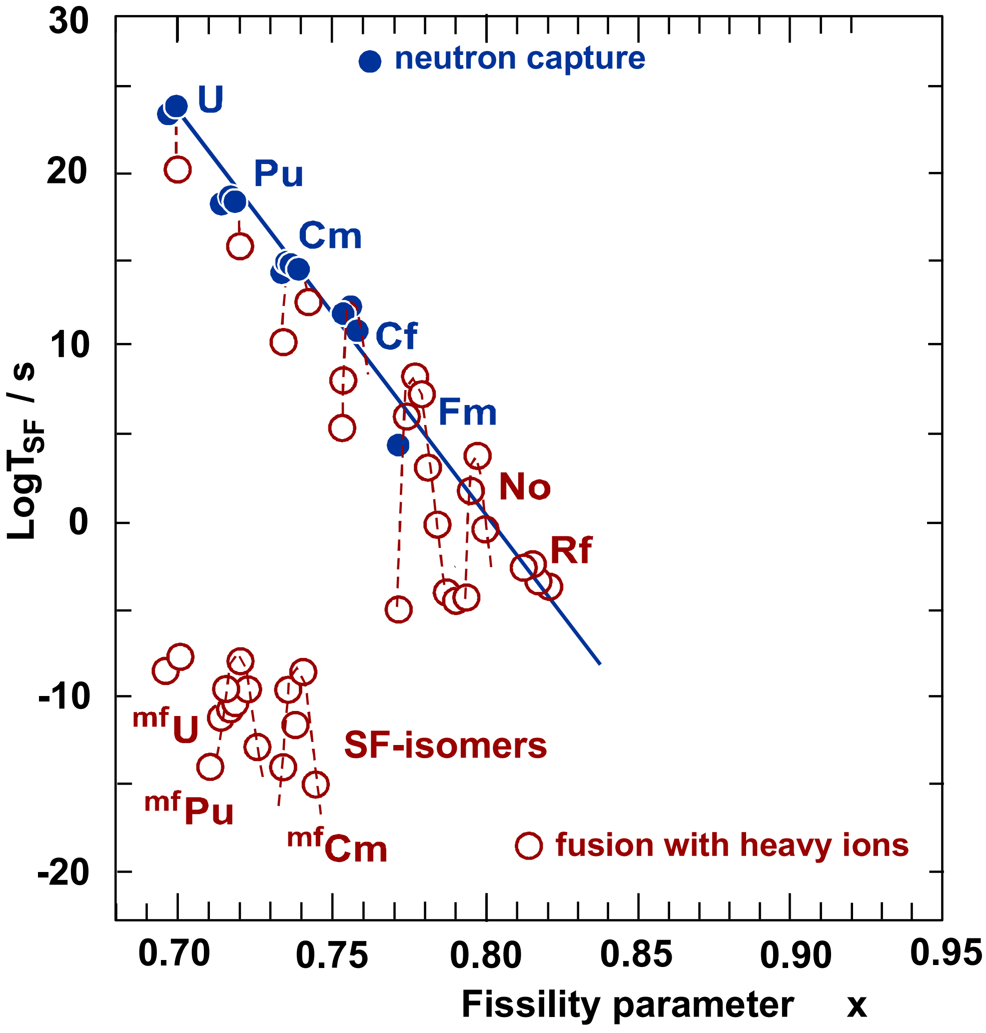
K.A. Petrzhak

Spontaneous Fission

Macroscopic theory (Liquid Drop Model)

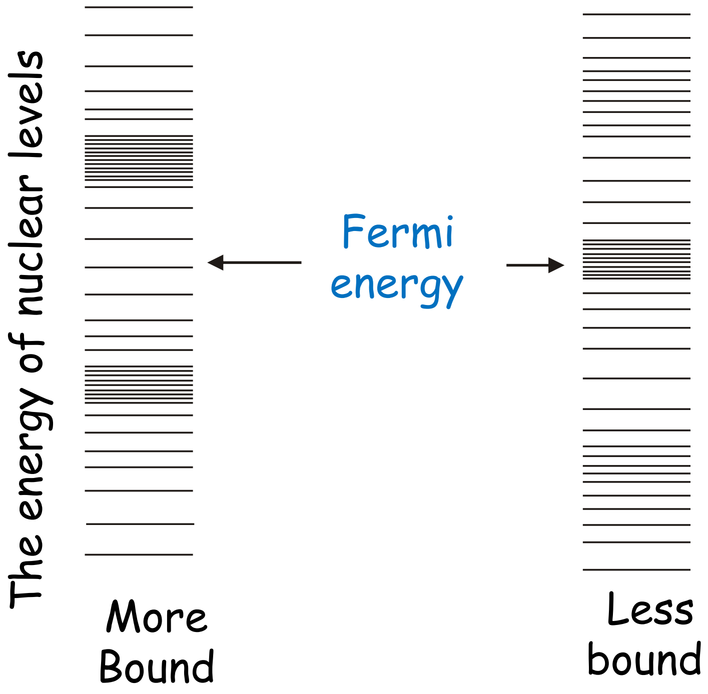
● ○ Exp.



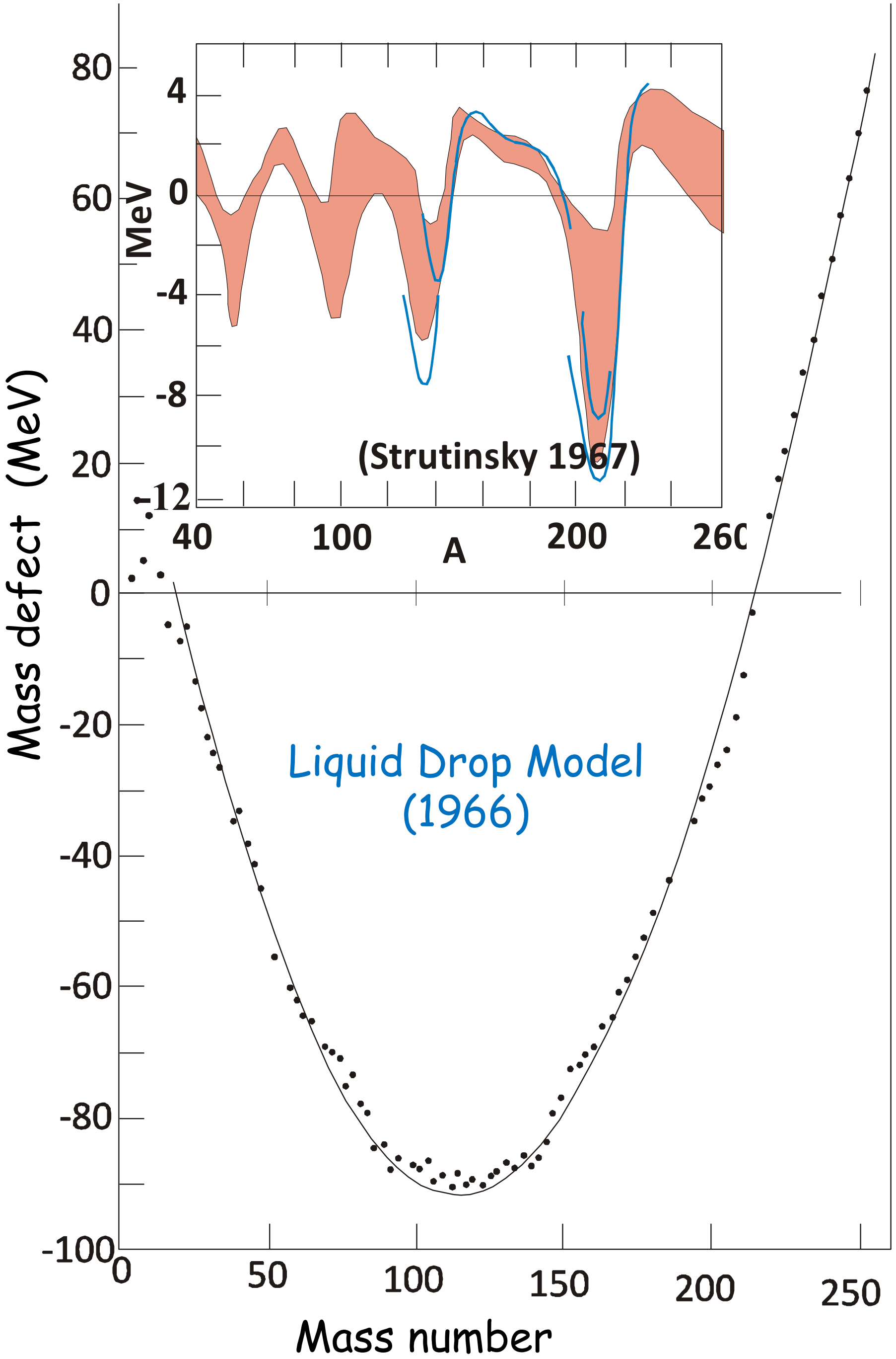


Nuclear Shells

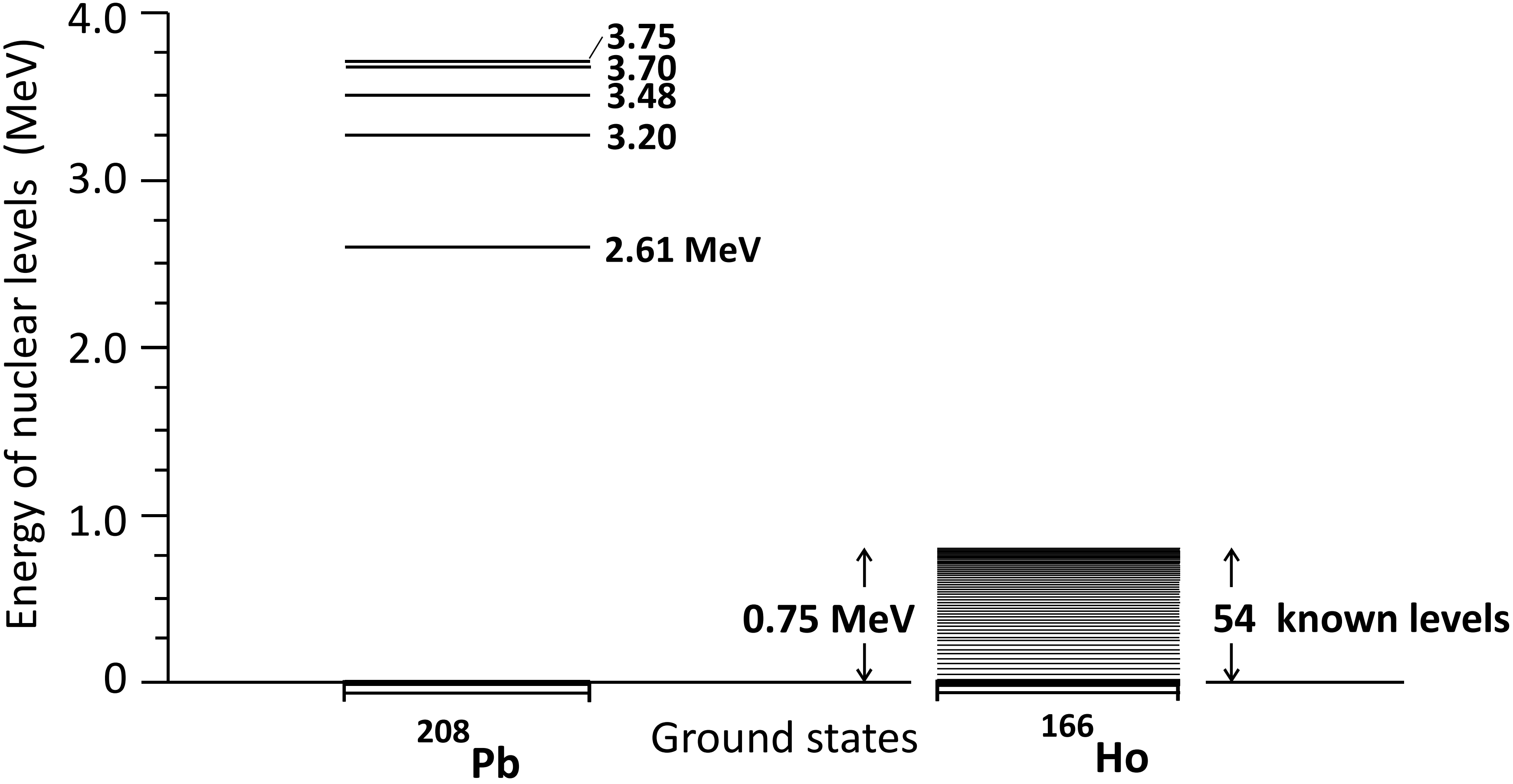
Shell correction



Fermi energy



Liquid Drop Model (1966)


Energy of nuclear levels (MeV)
4.0
3.0
2.0
1.0
0
3.75
3.70
3.48
3.20
2.61 MeV
0.75 MeV
54 known levels
208Pb
Ground states
166Ho

Shells and magic numbers

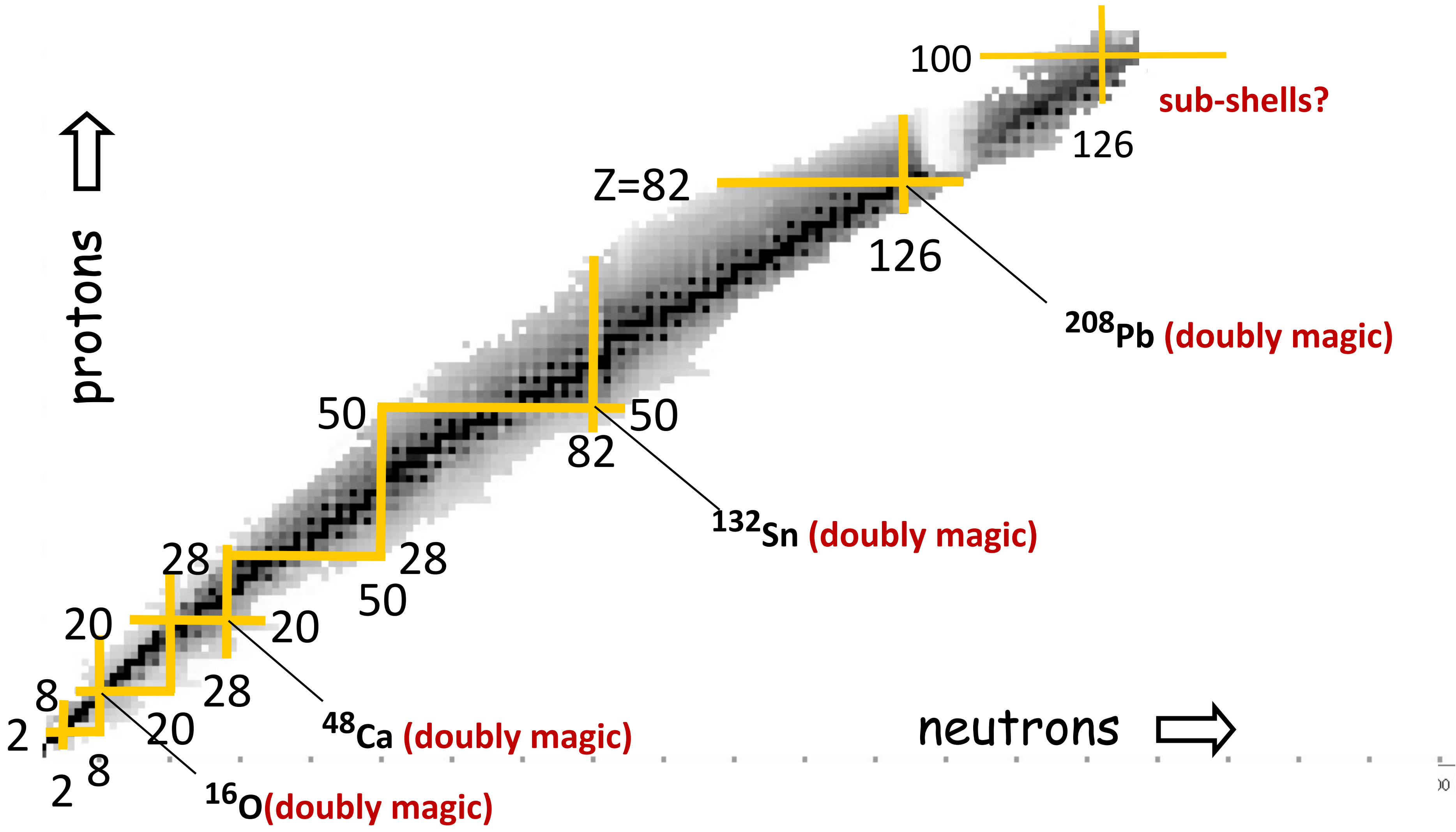
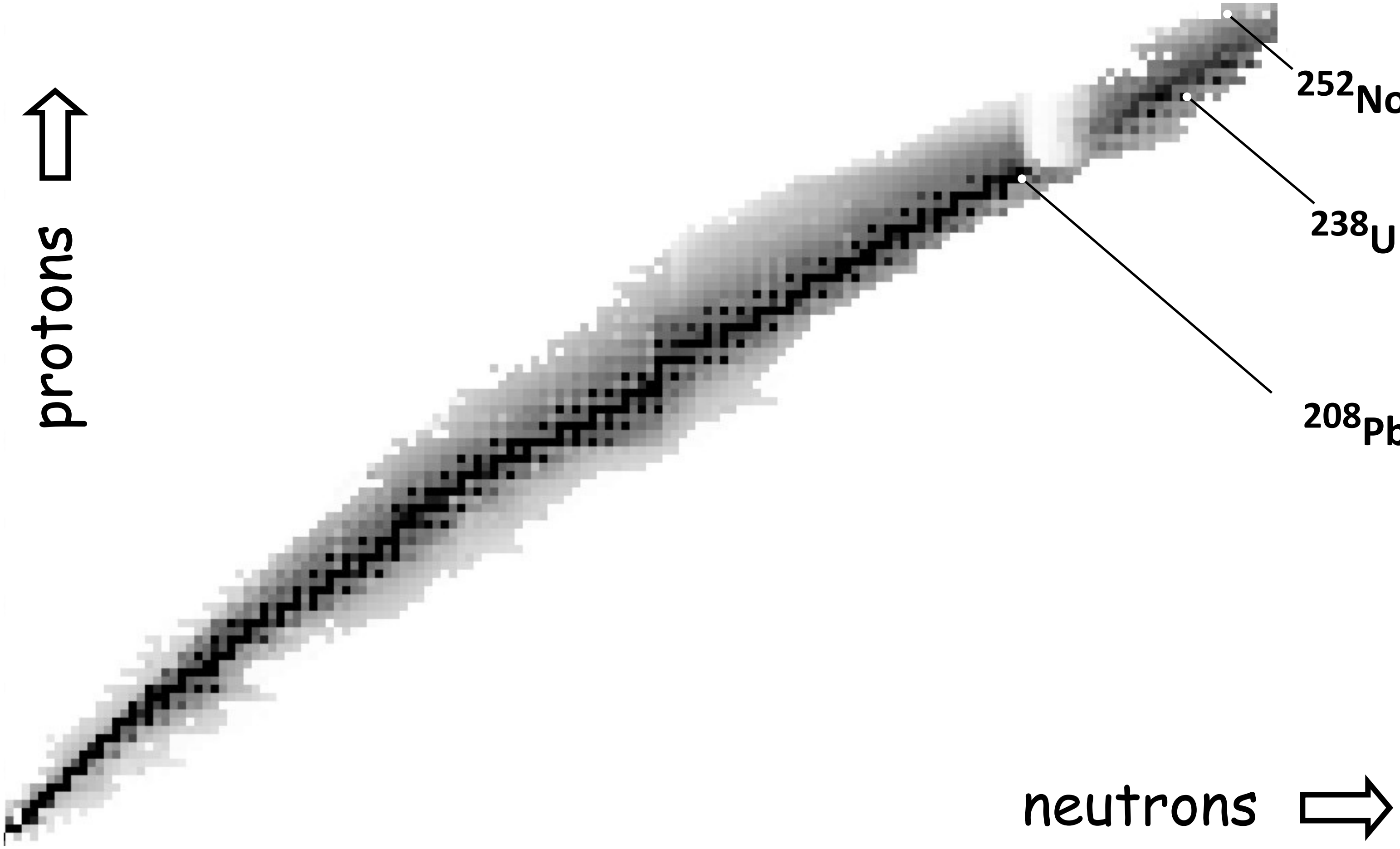


Chart of the Nuclides

SF



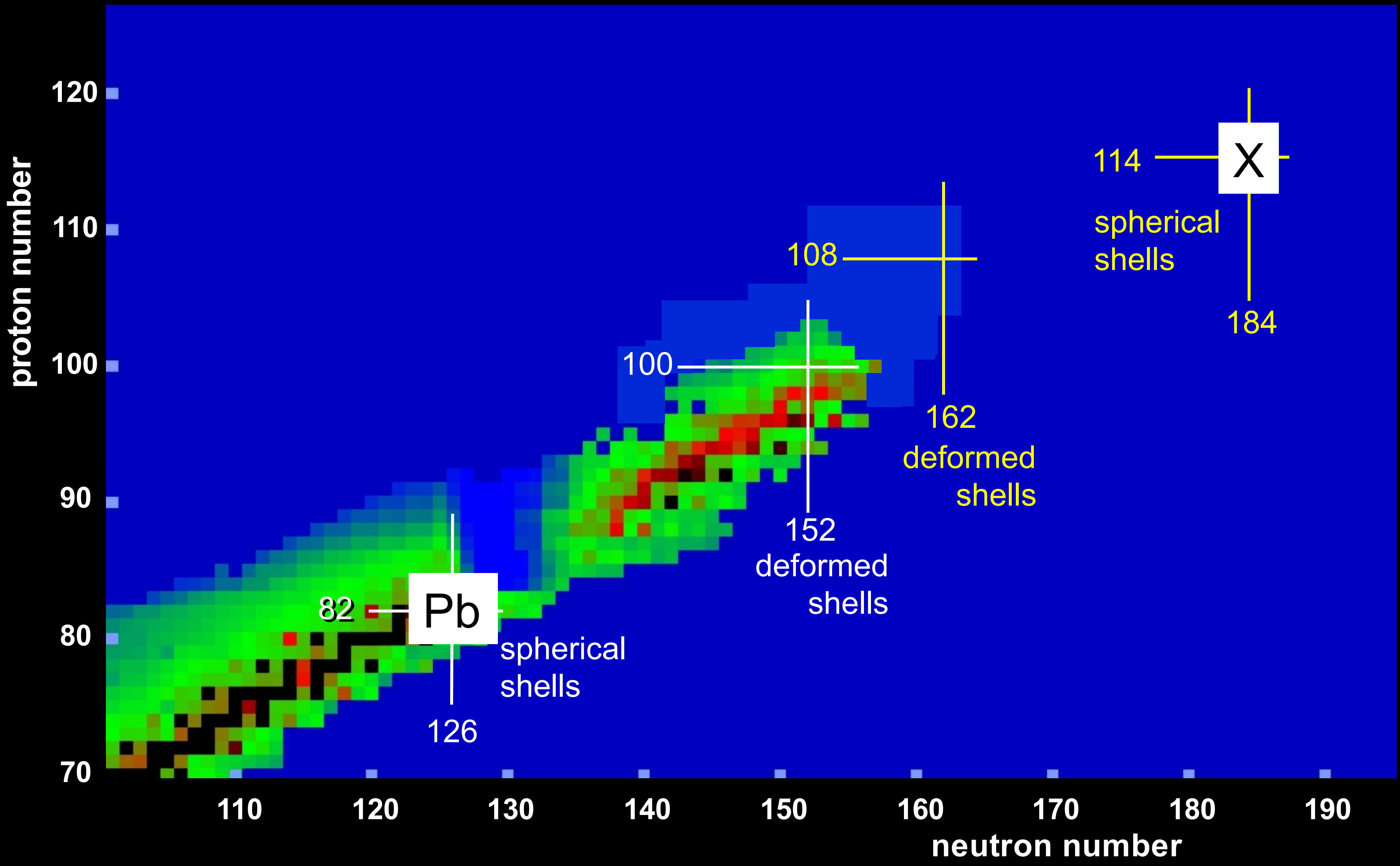
^{252}No $\alpha/2.3$ s
SF/ 7 s

^{238}U $\alpha/4.5\cdot10^{9}$y
SF/ 10^{16}y

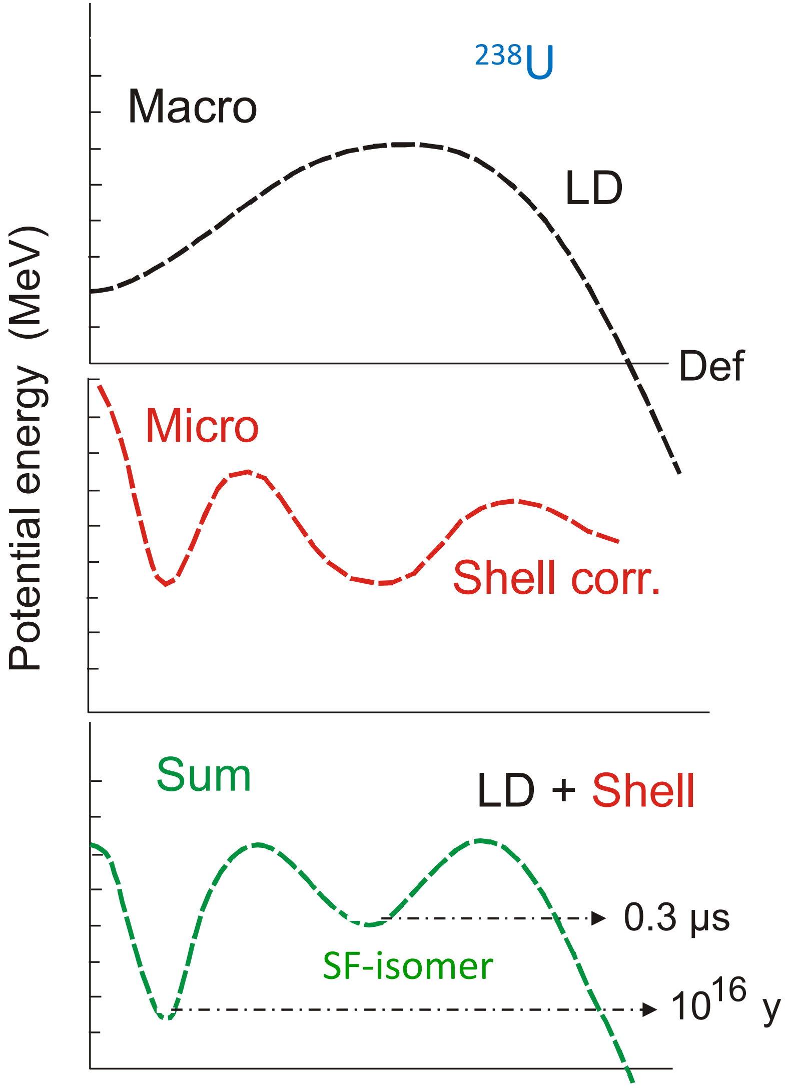
^{208}Pb stable

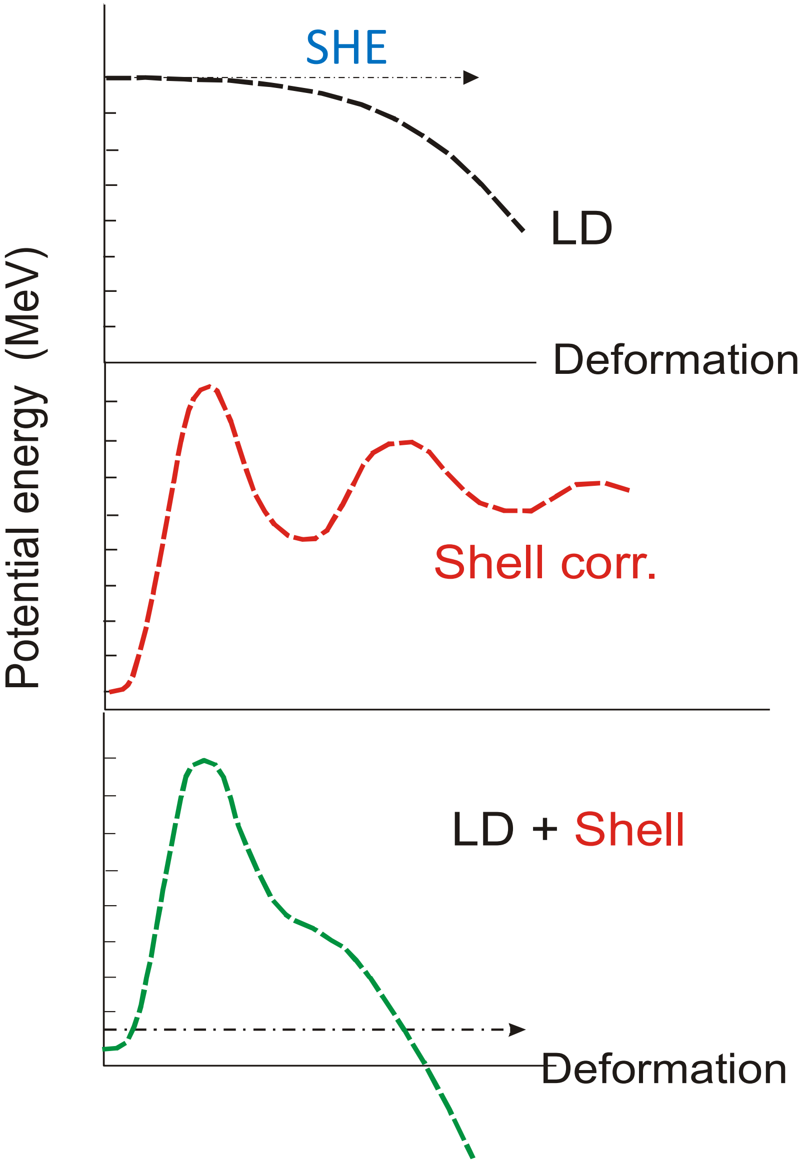
Chart of nuclides

Nuclear shells
(macro-microscopic approach)



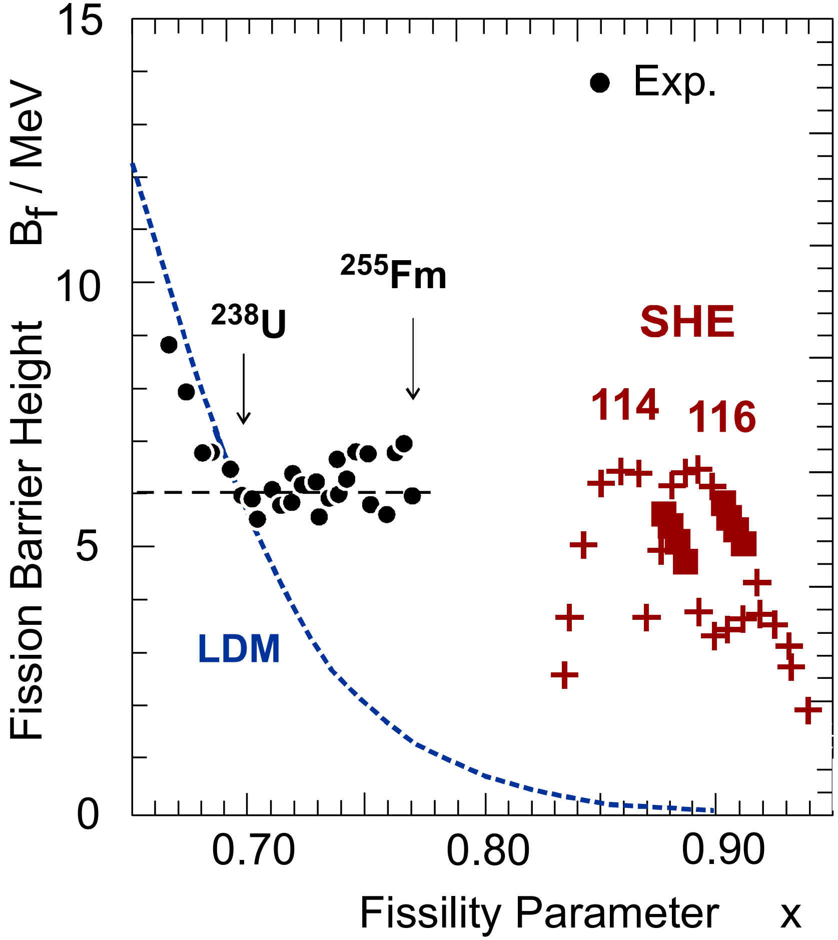
Microscopic corrections to the macroscopic nuclear deformation energy



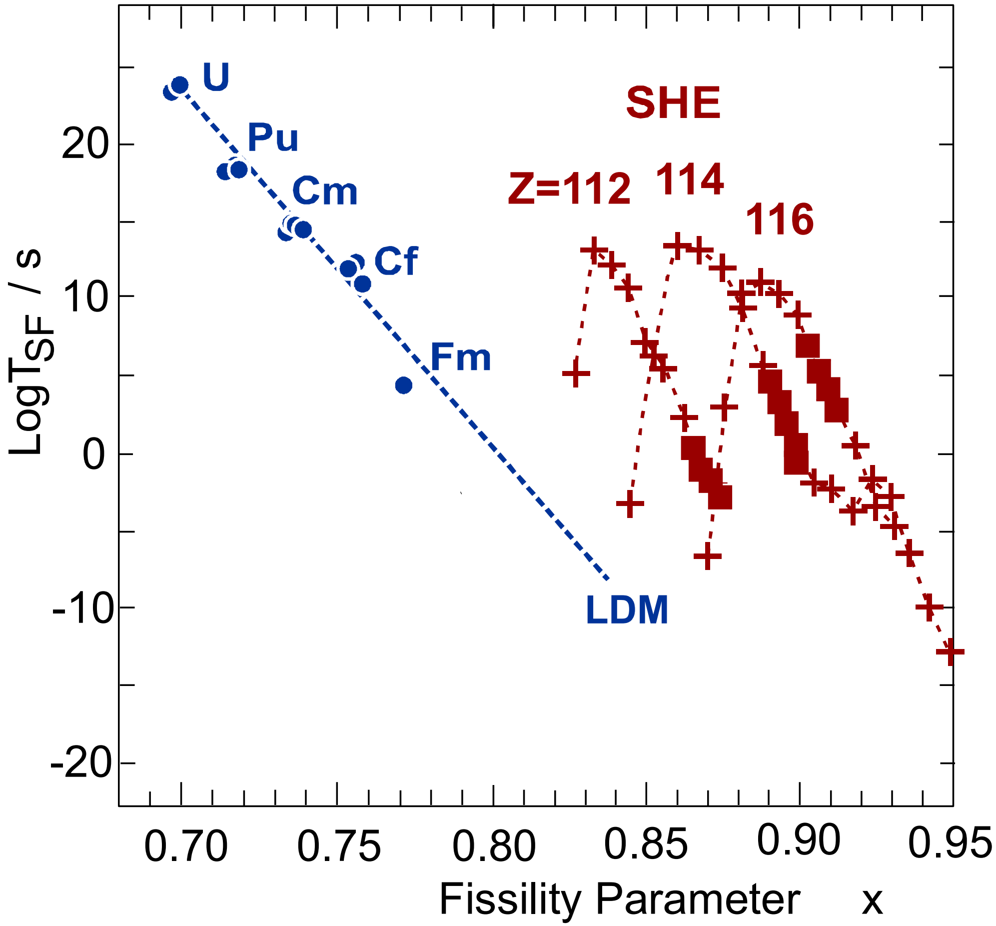


Predictions of the microscopic theory

Fission Barriers



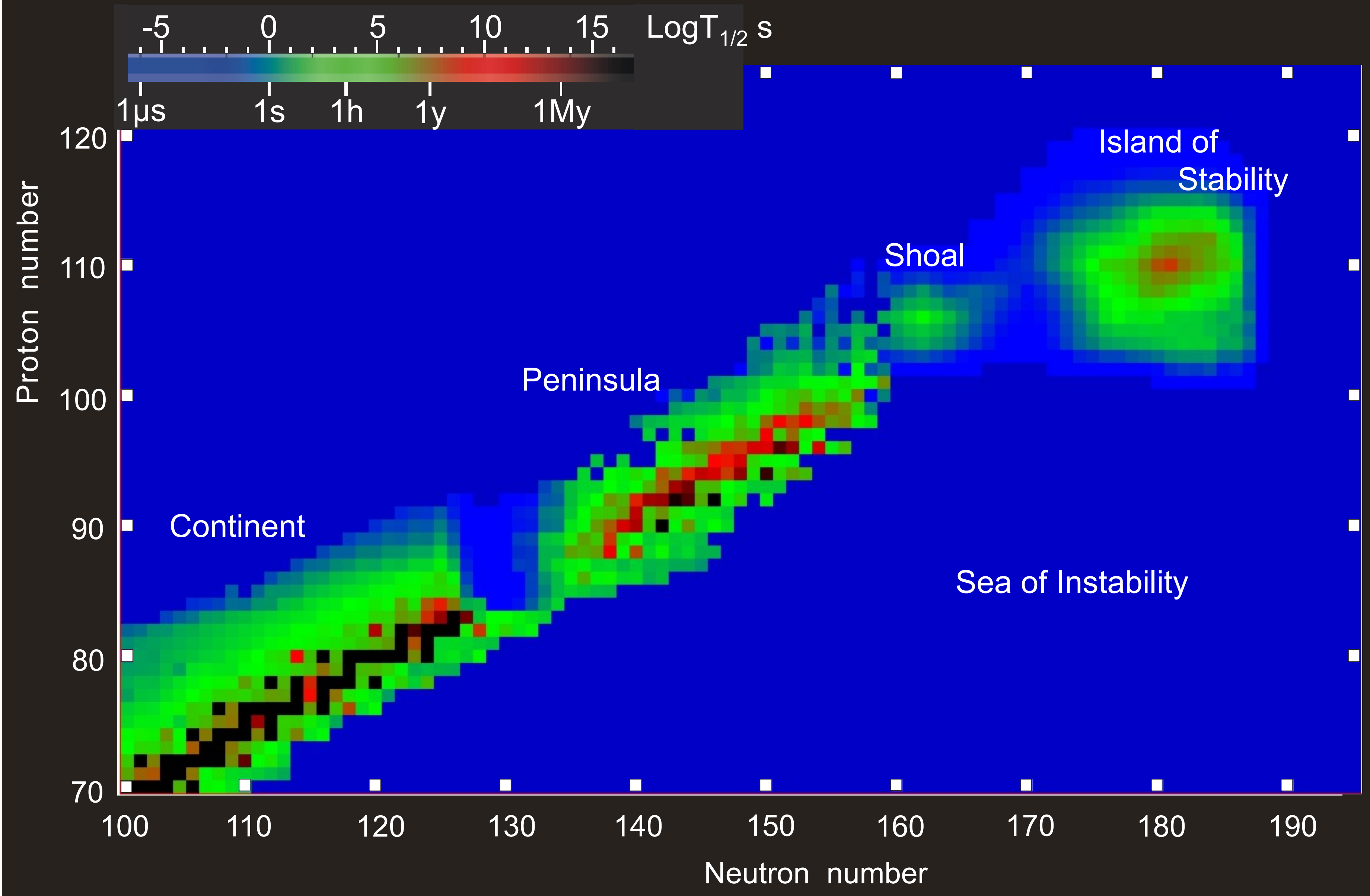
…and Half - Lives



R. Smolańczuk, Phys. Rev. C 56 (1997) 812

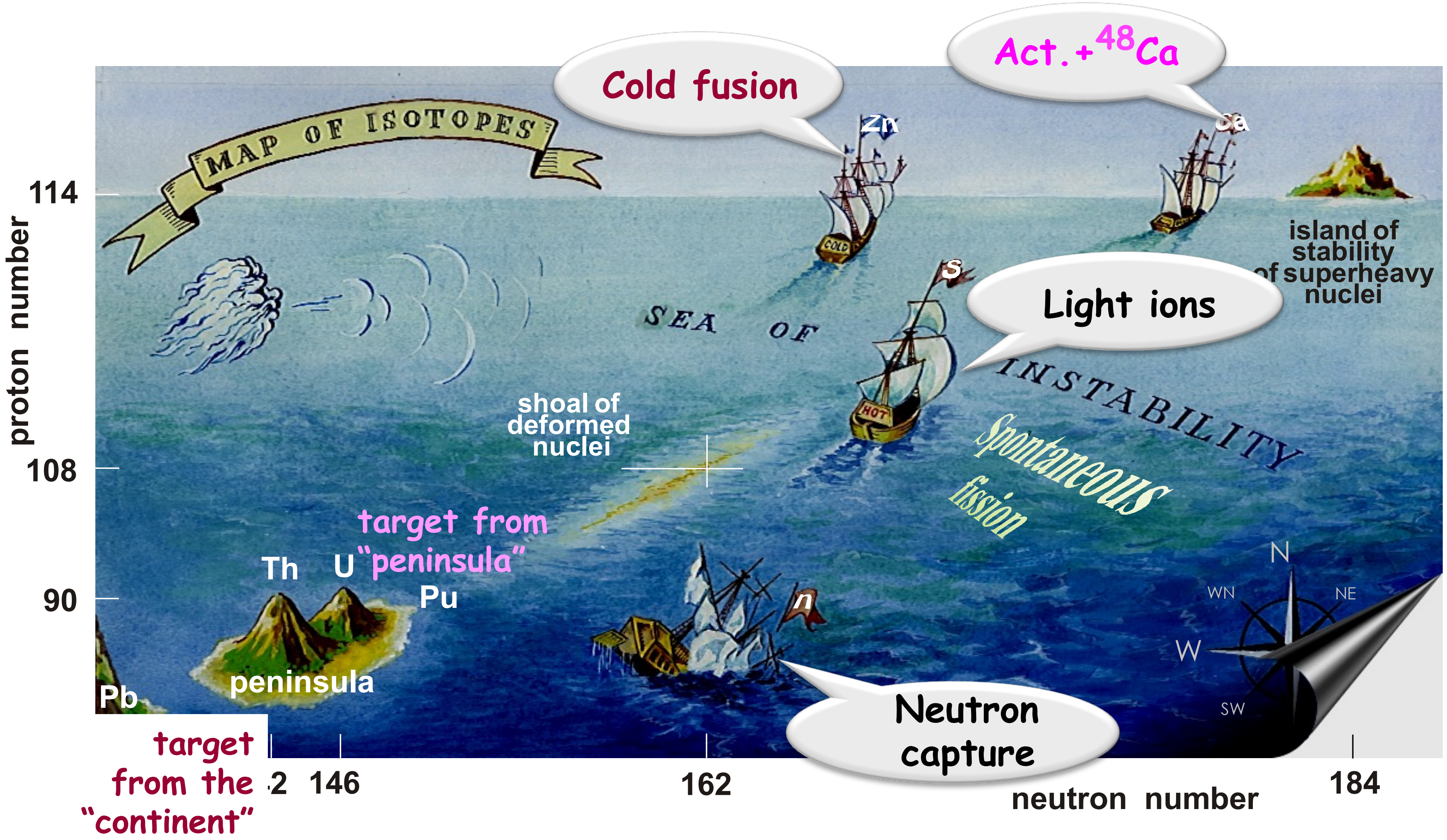
New lands

Microscopic theory



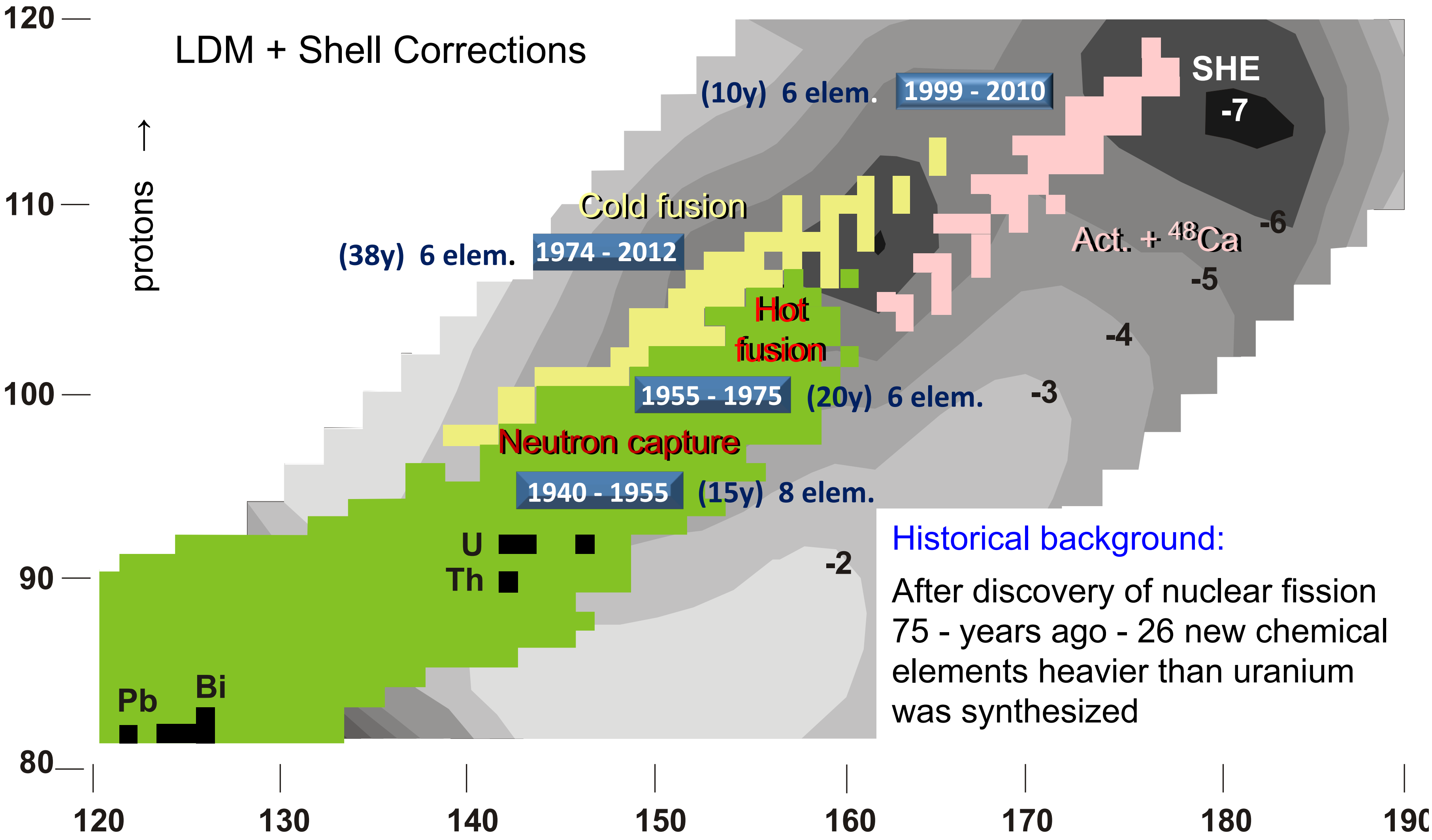
Reactions of Synthesis

Reactions of synthesis



Synthesis of the SHE

Reactions of Synthesis



A. Sobiczewski, K. Pomorski, PPNP 58, 292, 2007

Historical background:

After discovery of nuclear fission 75 - years ago - 26 new chemical elements heavier than uranium was synthesized

REACTIONS OF SYNTHESIS

48Ca - PROJECTILES

Energy:
235-250 MeV

Intensity:
1.0-1.2 pμA

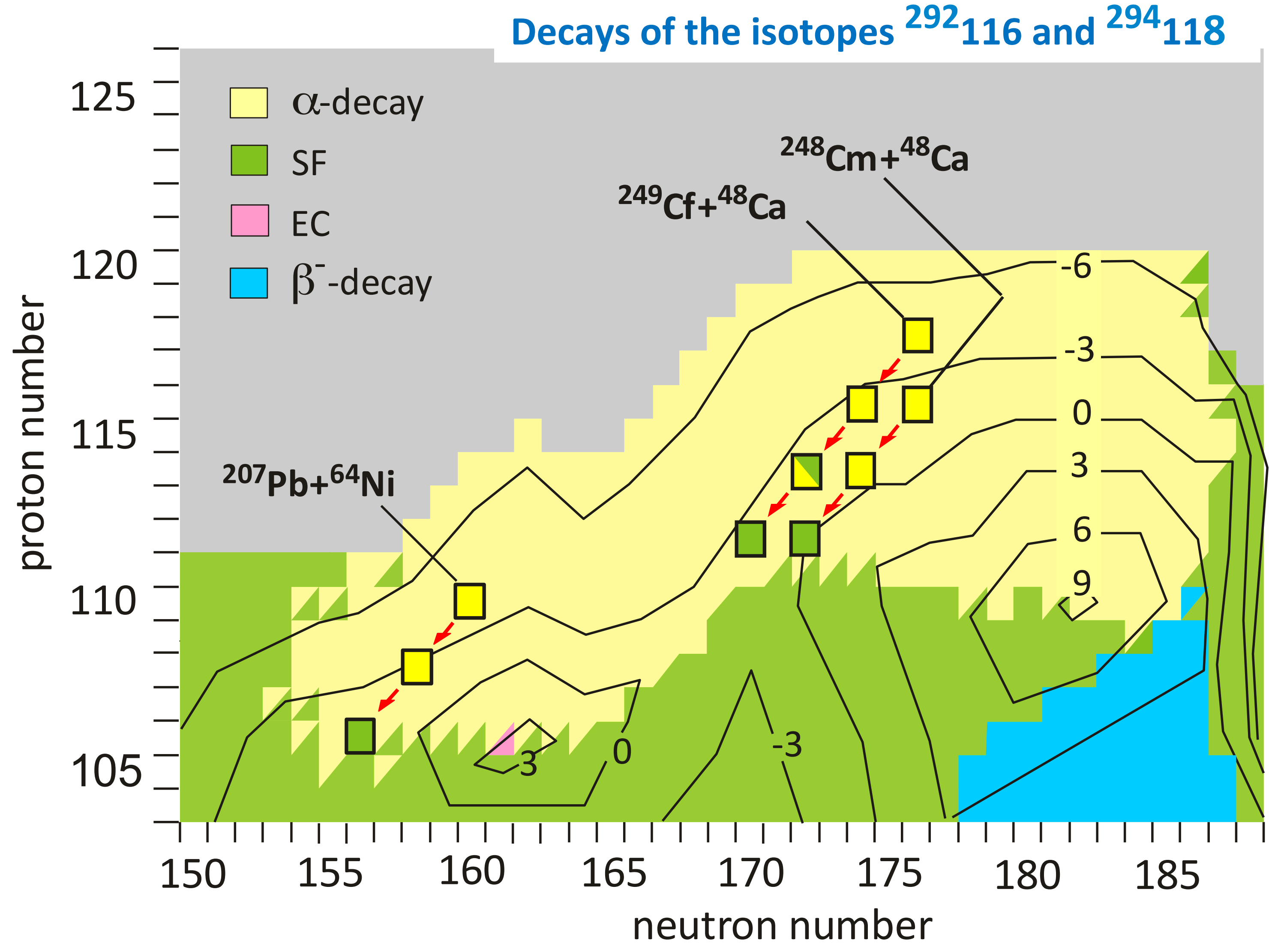
Consumption:
0.5 mg/h

Beam dose:
up to $4.5 \cdot 10^{19}$

TARGETS

Isotope	Target thickness mg/cm^2	Isotope enrichment %	Setup
233U	0.44	99.92	DGFRS
237Np	0.35	99.3	DGFRS
238U	0.35	99.3	DGFRS
242Pu	0.40	99.98	DGFRS
	1.40	99.98	Chem.
243Am	0.36	99.9	DGFRS
	1.20	99.9	Chem.
244Pu	0.38	98.6	DGFRS
245Cm	0.35	98.7	DGFRS
248Cm	0.35	97.4	DGFRS
249Bk	0.35	≥90	DGFRS
249Cf	0.30	98.3	DGFRS

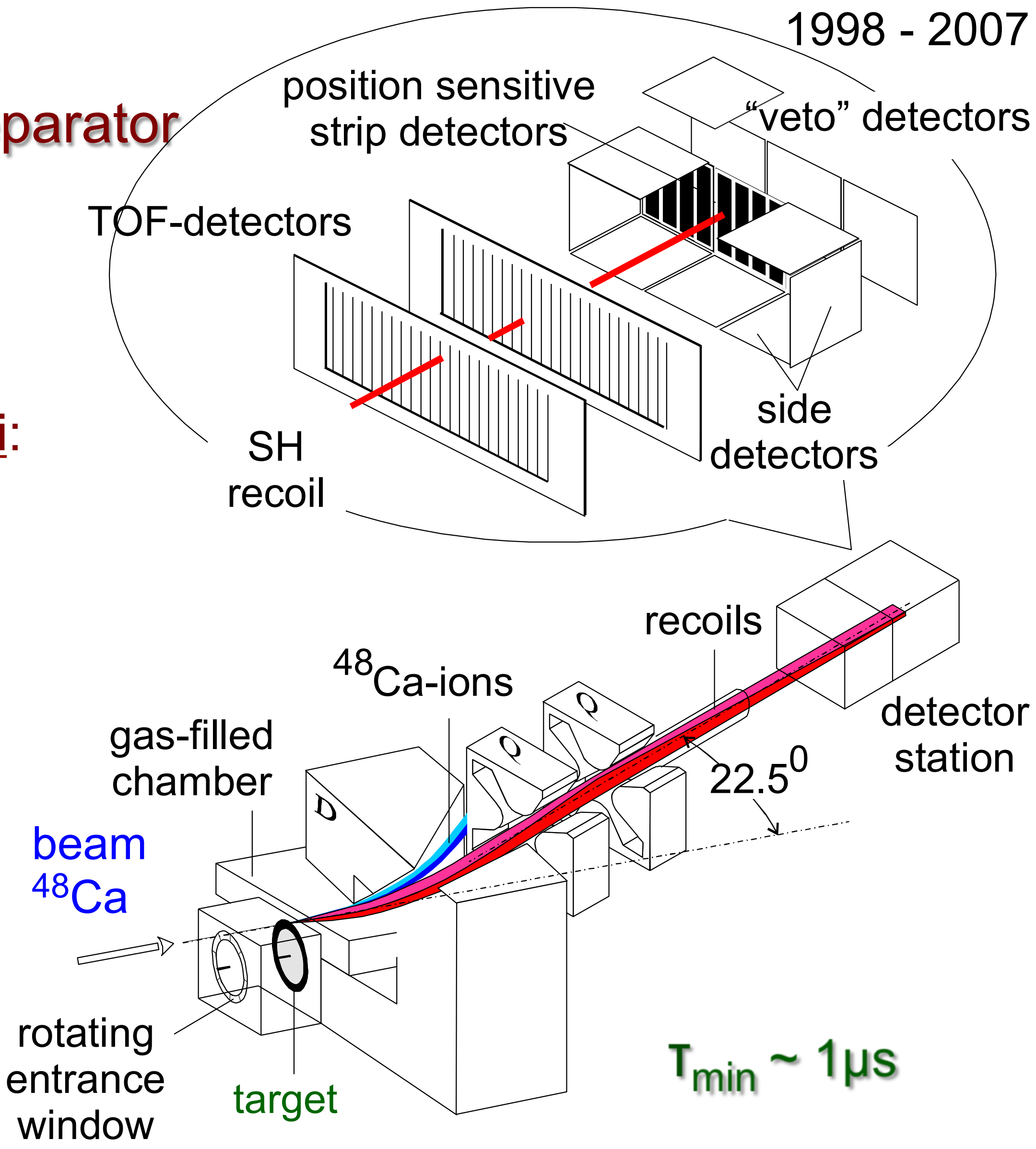
Contour map of the calculated half-lives as Log$T_{1/2}$ (in seconds) and decay modes of nuclei with different proton and neutron numbers



Decays of the isotopes $^{292}116$ and $^{294}118$

Experimental technique

Dubna Gas-Filled Recoil Separator



Transmission for:

EVR 35-40%

Suppression of unwanted nuclei:

target-like 10^{-4}-10^{-7}

projectile-like 10^{-15}-10^{-17}

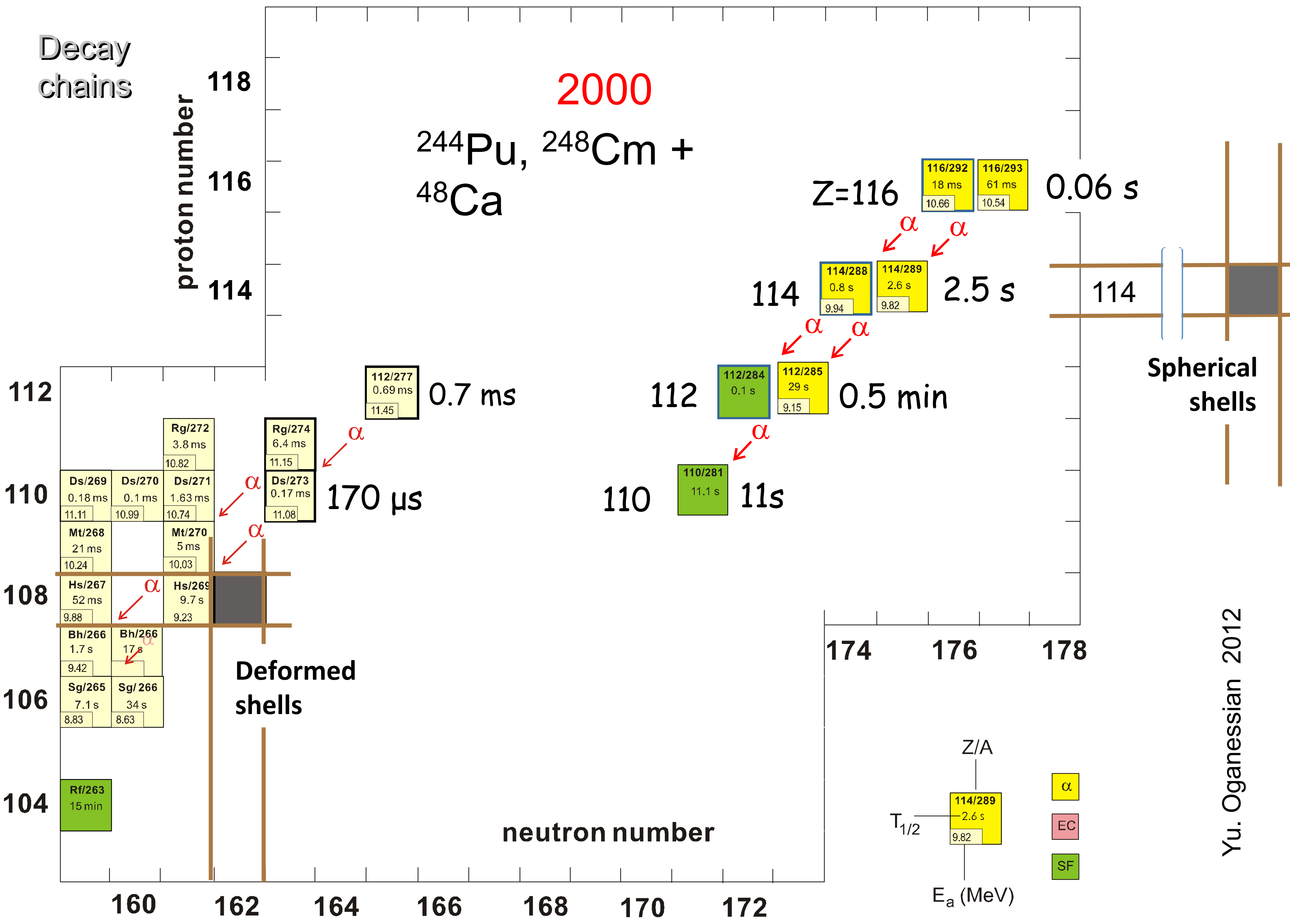
Registration efficiency:

for α-particles 87%

for SF
- single fragment 100%
- two fragments ≈ 40%

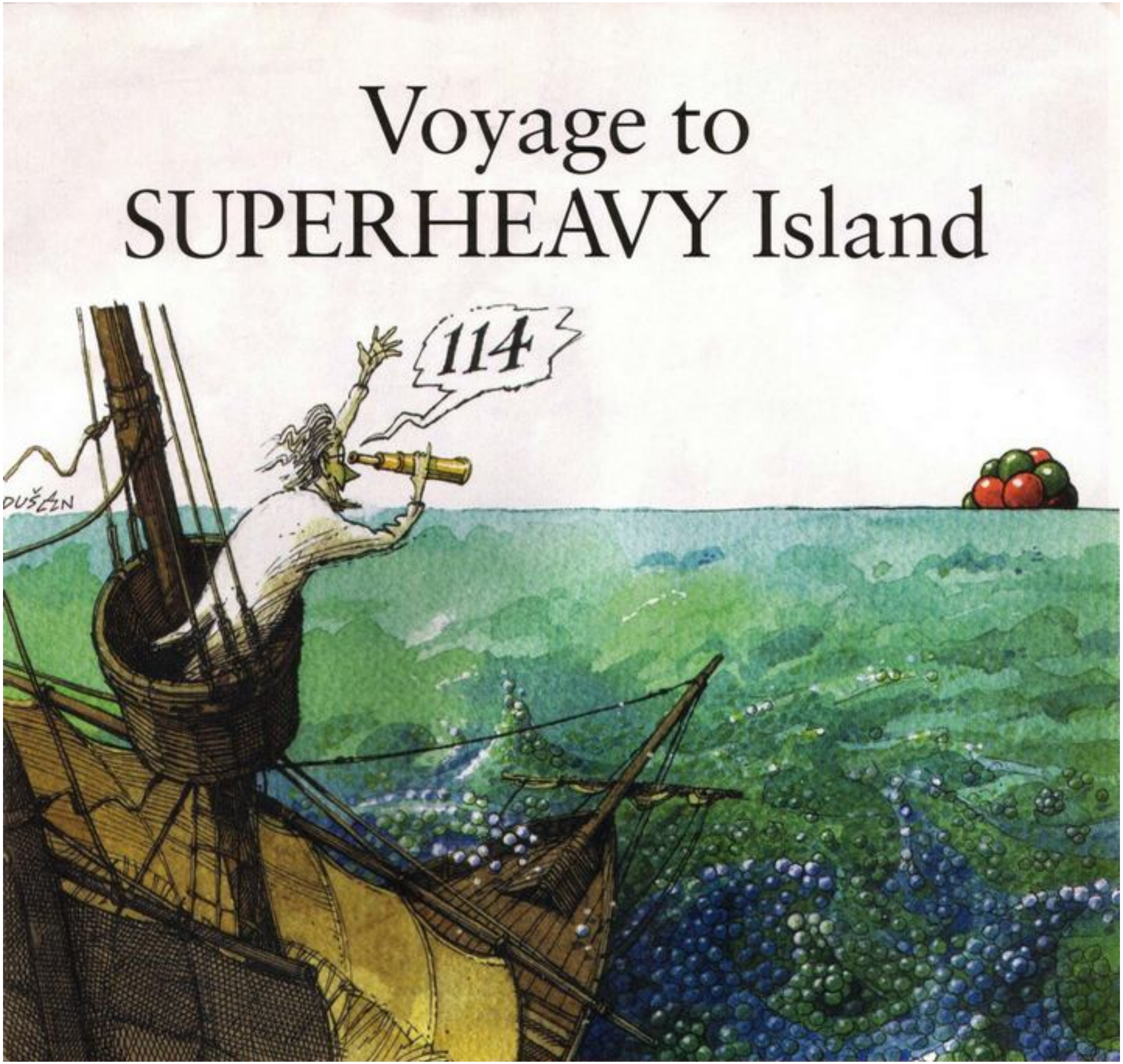
T_{min} ~ 1μs

Decay chains



SCIENTIFIC AMERICAN

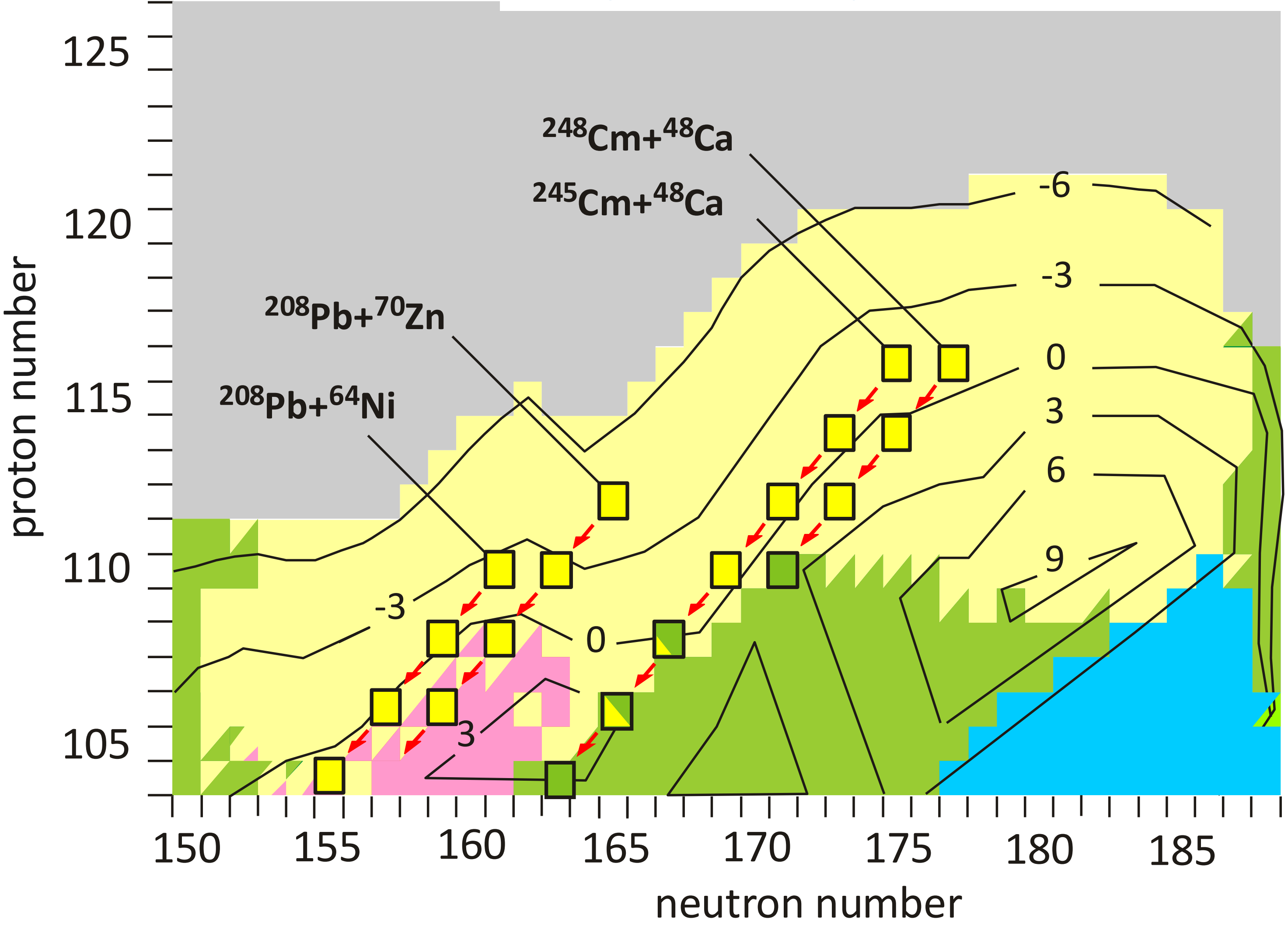
JANUARY 2000 VOL. 282 NO 1



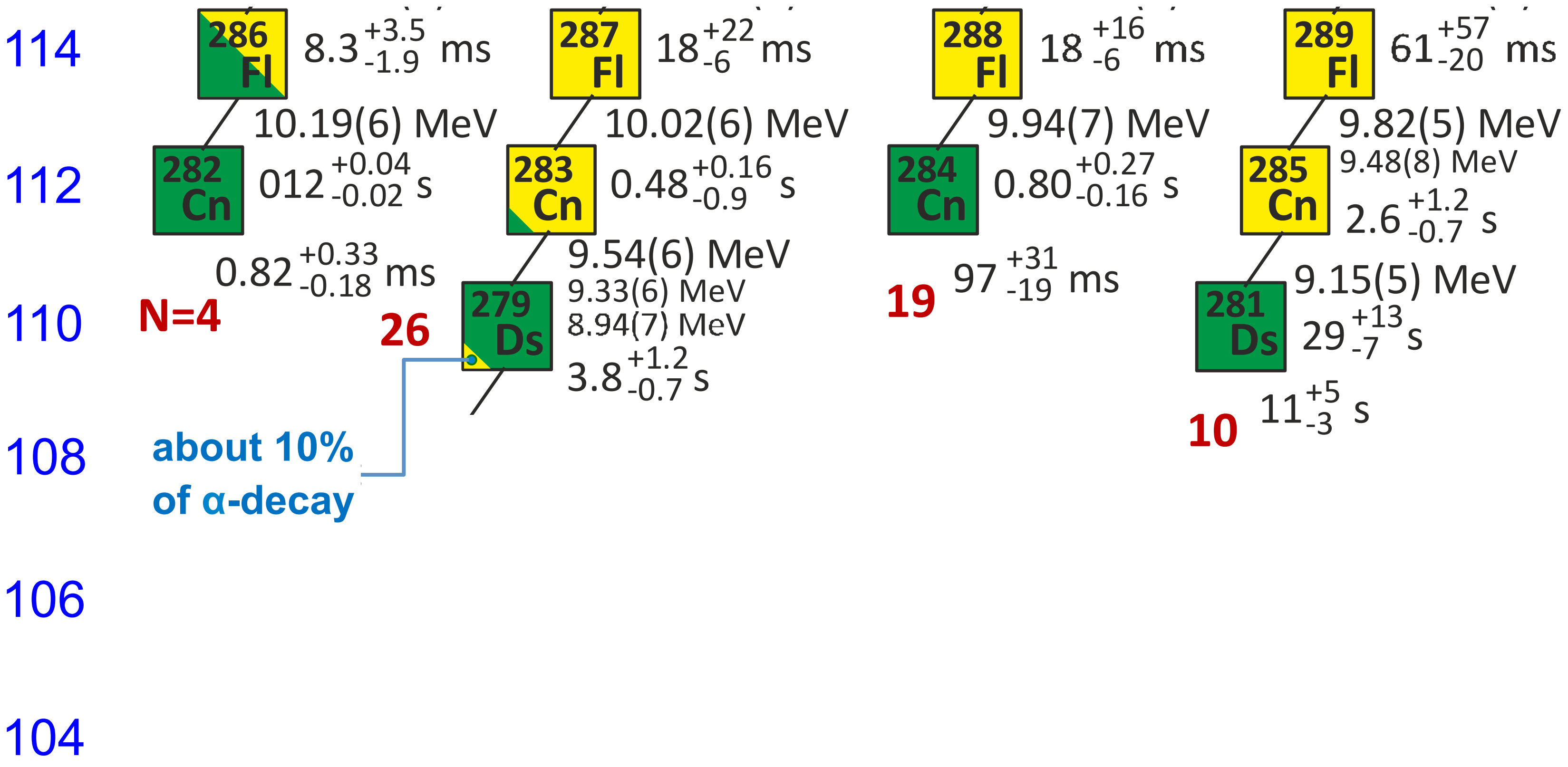
Decay Properties

Z-even Nuclei

Decays of the isotopes $^{291}116$ and $^{293}116$



Decay Chains of the Isotopes of Element 114



114
112
110
108
106
104

286 Fl $8.3^{+3.5}_{-1.9}$ ms
10.19(6) MeV
282 Cn $012^{+0.04}_{-0.02}$ s
$0.82^{+0.33}_{-0.18}$ ms
N=4

287 Fl 18^{+22}_{-6} ms
10.02(6) MeV
283 Cn $0.48^{+0.16}_{-0.9}$ s
9.54(6) MeV
9.33(6) MeV
8.94(7) MeV
279 Ds $3.8^{+1.2}_{-0.7}$ s
26

about 10%
of α-decay

288 Fl 18^{+16}_{-6} ms
9.94(7) MeV
284 Cn $0.80^{+0.27}_{-0.16}$ s
19 97^{+31}_{-19} ms

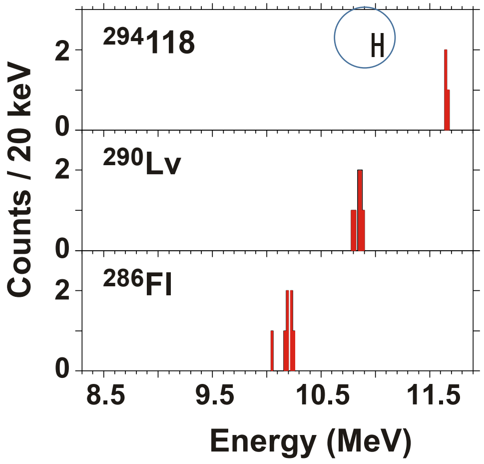
289 Fl 61^{+57}_{-20} ms
9.82(5) MeV
285 Cn
9.48(8) MeV
$2.6^{+1.2}_{-0.7}$ s
9.15(5) MeV
281 Ds 29^{+13}_{-7} s
10 11^{+5}_{-3} s

Even Z Nuclei

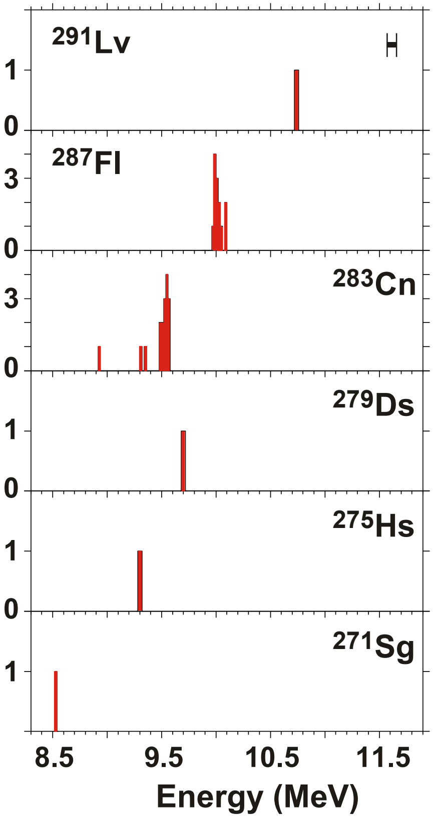
1999 - 2005

Energy spectra of alpha particles

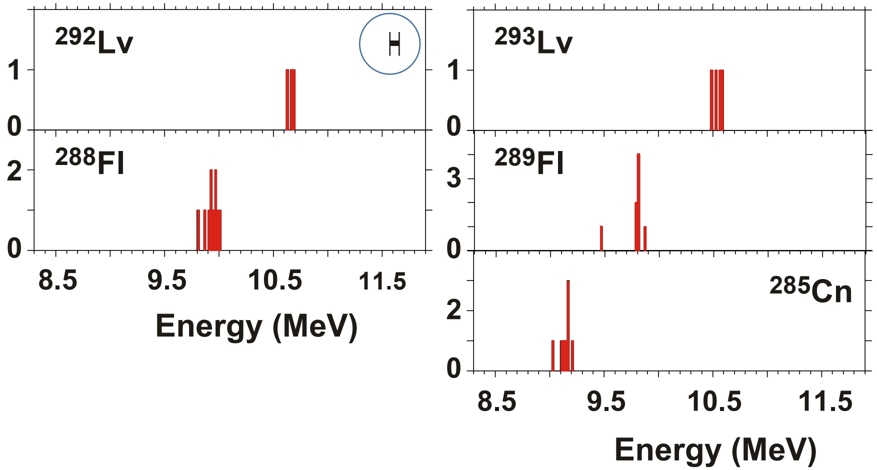
^{249}Cf + ^{48}Ca



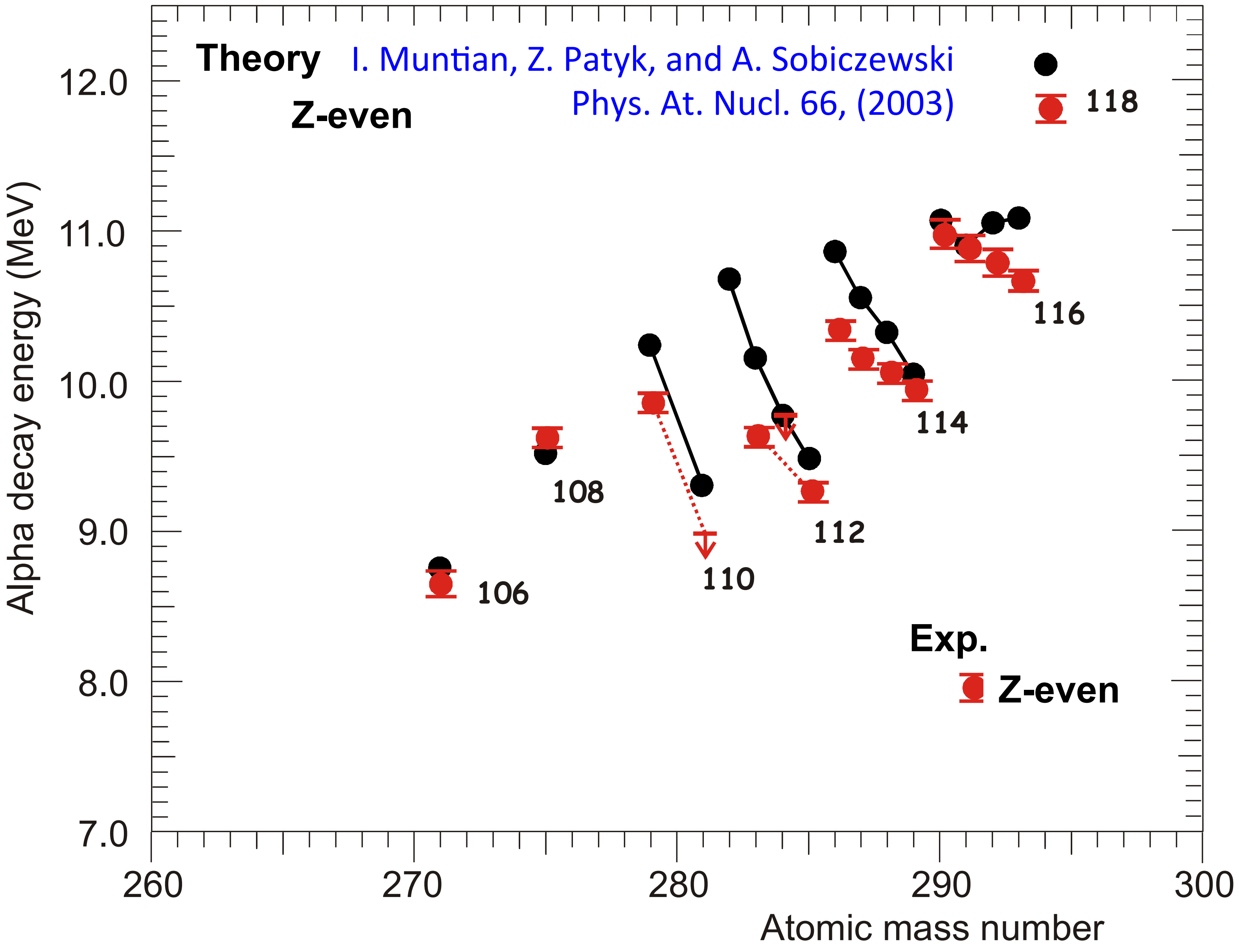
^{242}Pu+ ^{48}Ca



^{244}Pu+ ^{48}Ca

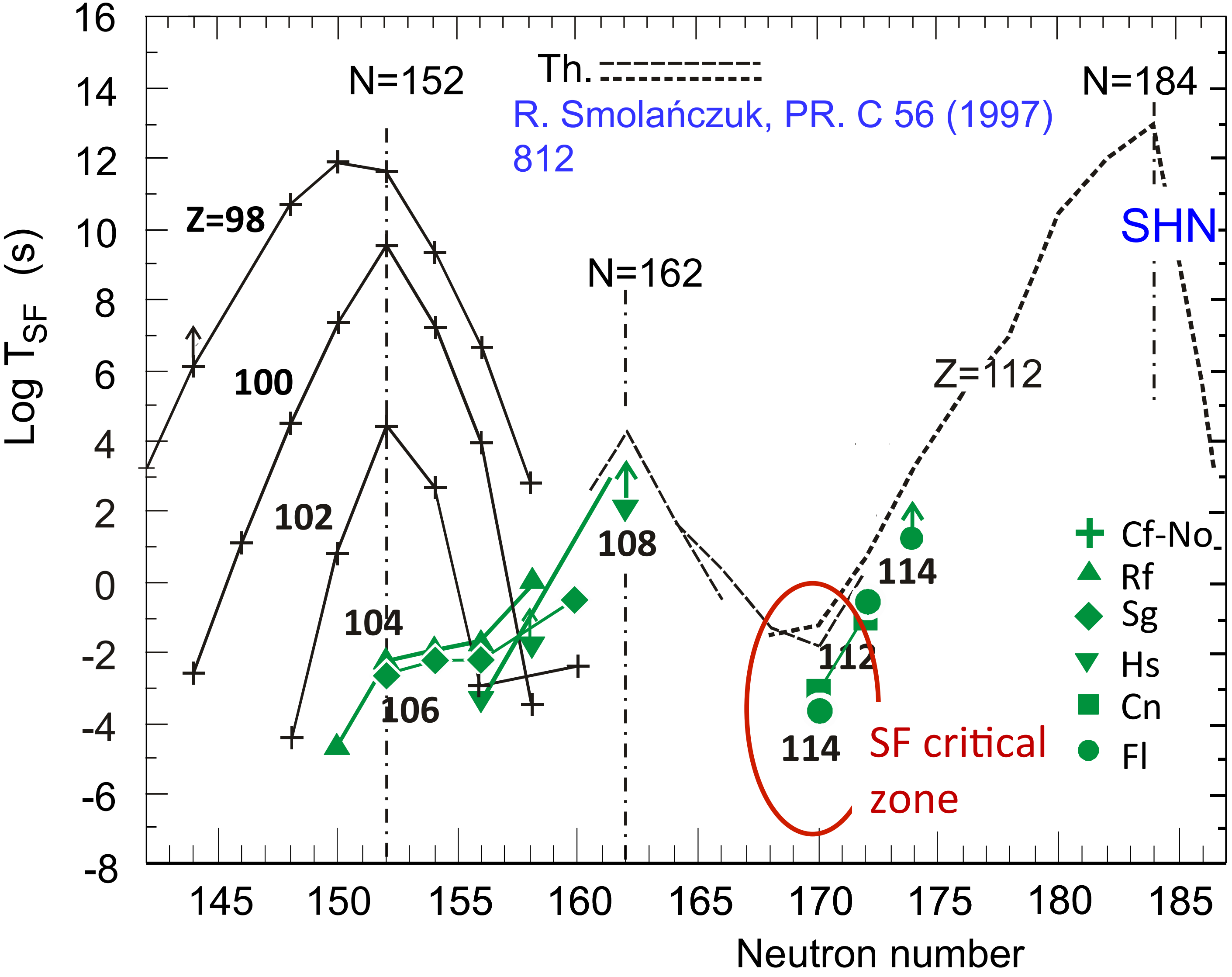


Alpha - decay


Theory
I. Muntian, Z. Patyk, and A. Sobiczewski
Phys. At. Nucl. 66, (2003)
Z-even
118
116
114
112
110
108
106
Exp.
Z-even
Alpha decay energy (MeV)
12.0
11.0
10.0
9.0
8.0
7.0
260
270
280
290
300
Atomic mass number

Spontaneous fission

even-even isotopes

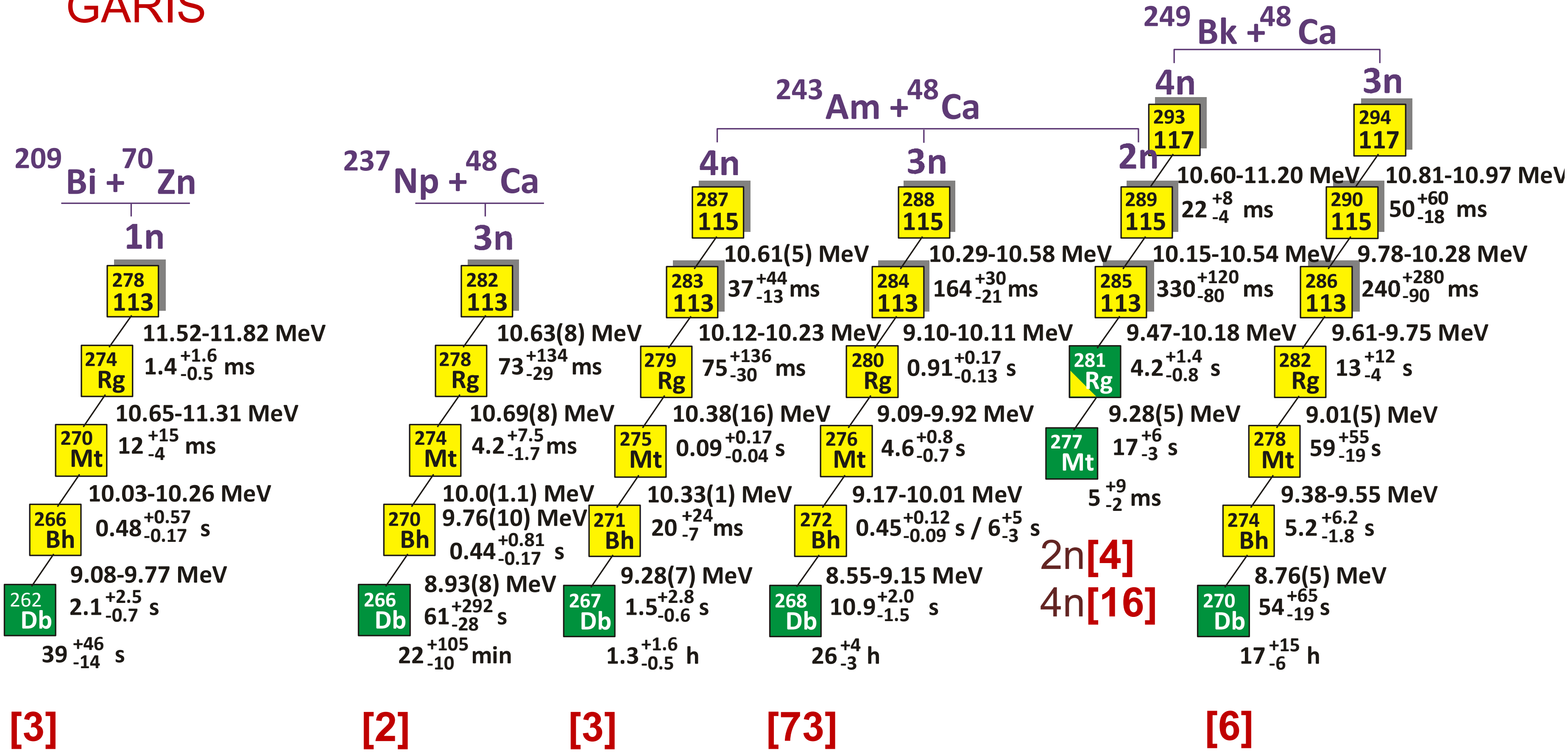


R. Smolańczuk, PR. C 56 (1997) 812

June, 2013

DGFRS + TASCA

GARIS



^{209}Bi + ^{70}Zn
1n
$^{278}113$
11.52-11.82 MeV
^{274}Rg $1.4^{+1.6}_{-0.5}$ ms
10.65-11.31 MeV
^{270}Mt 12^{+15}_{-4} ms
10.03-10.26 MeV
^{266}Bh $0.48^{+0.57}_{-0.17}$ s
9.08-9.77 MeV
^{262}Db $2.1^{+2.5}_{-0.7}$ s
39^{+46}_{-14} s
[3]

^{237}Np + ^{48}Ca
3n
$^{282}113$
10.63(8) MeV
^{278}Rg 73^{+134}_{-29} ms
10.69(8) MeV
^{274}Mt $4.2^{+7.5}_{-1.7}$ ms
10.0(1.1) MeV
9.76(10) MeV
^{270}Bh $0.44^{+0.81}_{-0.17}$ s
8.93(8) MeV
^{266}Db 61^{+292}_{-28} s
22^{+105}_{-10} min
[2]

^{243}Am + ^{48}Ca

4n
$^{287}115$
10.61(5) MeV
$^{283}113$ 37^{+44}_{-13} ms
10.12-10.23 MeV
^{279}Rg 75^{+136}_{-30} ms
10.38(16) MeV
^{275}Mt $0.09^{+0.17}_{-0.04}$ s
10.33(1) MeV
^{271}Bh 20^{+24}_{-7} ms
9.28(7) MeV
^{267}Db $1.5^{+2.8}_{-0.6}$ s
$1.3^{+1.6}_{-0.5}$ h
[3]

3n
$^{288}115$
10.29-10.58 MeV
$^{284}113$ 164^{+30}_{-21} ms
9.10-10.11 MeV
^{280}Rg $0.91^{+0.17}_{-0.13}$ s
9.09-9.92 MeV
^{276}Mt $4.6^{+0.8}_{-0.7}$ s
9.17-10.01 MeV
^{272}Bh $0.45^{+0.12}_{-0.09}$ s / 6^{+5}_{-3} s
8.55-9.15 MeV
^{268}Db $10.9^{+2.0}_{-1.5}$ s
26^{+4}_{-3} h
[73]

2n
$^{289}115$ 22^{+8}_{-4} ms
10.15-10.54 MeV
$^{285}113$ 330^{+120}_{-80} ms
9.47-10.18 MeV
^{281}Rg $4.2^{+1.4}_{-0.8}$ s
9.28(5) MeV
^{277}Mt 17^{+6}_{-3} s
5^{+9}_{-2} ms

2n[4]
4n[16]

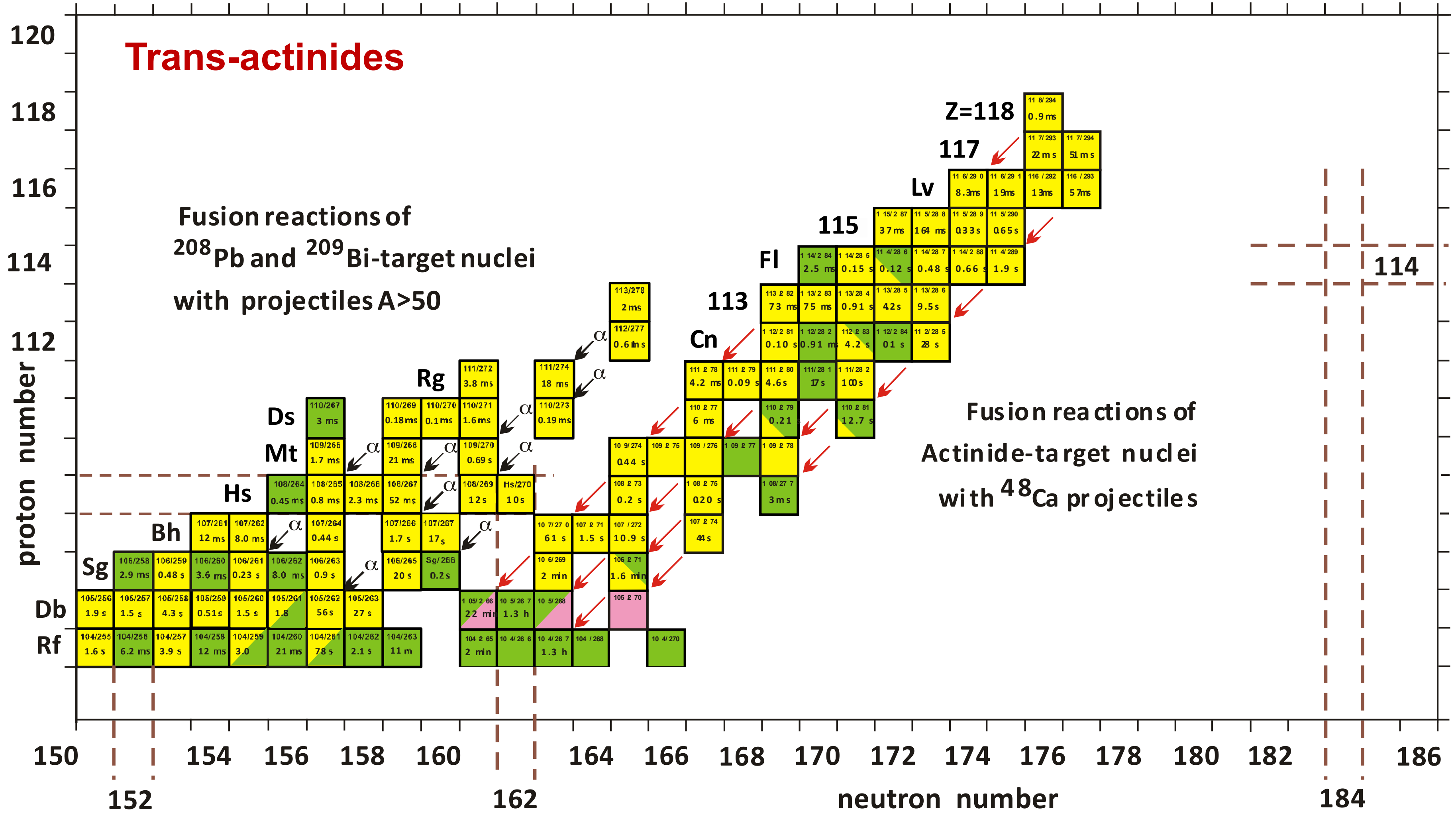
^{249}Bk + ^{48}Ca

4n
$^{293}117$
10.60-11.20 MeV

3n
$^{294}117$
10.81-10.97 MeV
$^{290}115$ 50^{+60}_{-18} ms
9.78-10.28 MeV
$^{286}113$ 240^{+280}_{-90} ms
9.61-9.75 MeV
^{282}Rg 13^{+12}_{-4} s
9.01(5) MeV
^{278}Mt 59^{+55}_{-19} s
9.38-9.55 MeV
^{274}Bh $5.2^{+6.2}_{-1.8}$ s
8.76(5) MeV
^{270}Db 54^{+65}_{-19} s
17^{+15}_{-6} h
[6]

RIKEN (Japan)

Map of the nuclides with Z ≥ 104



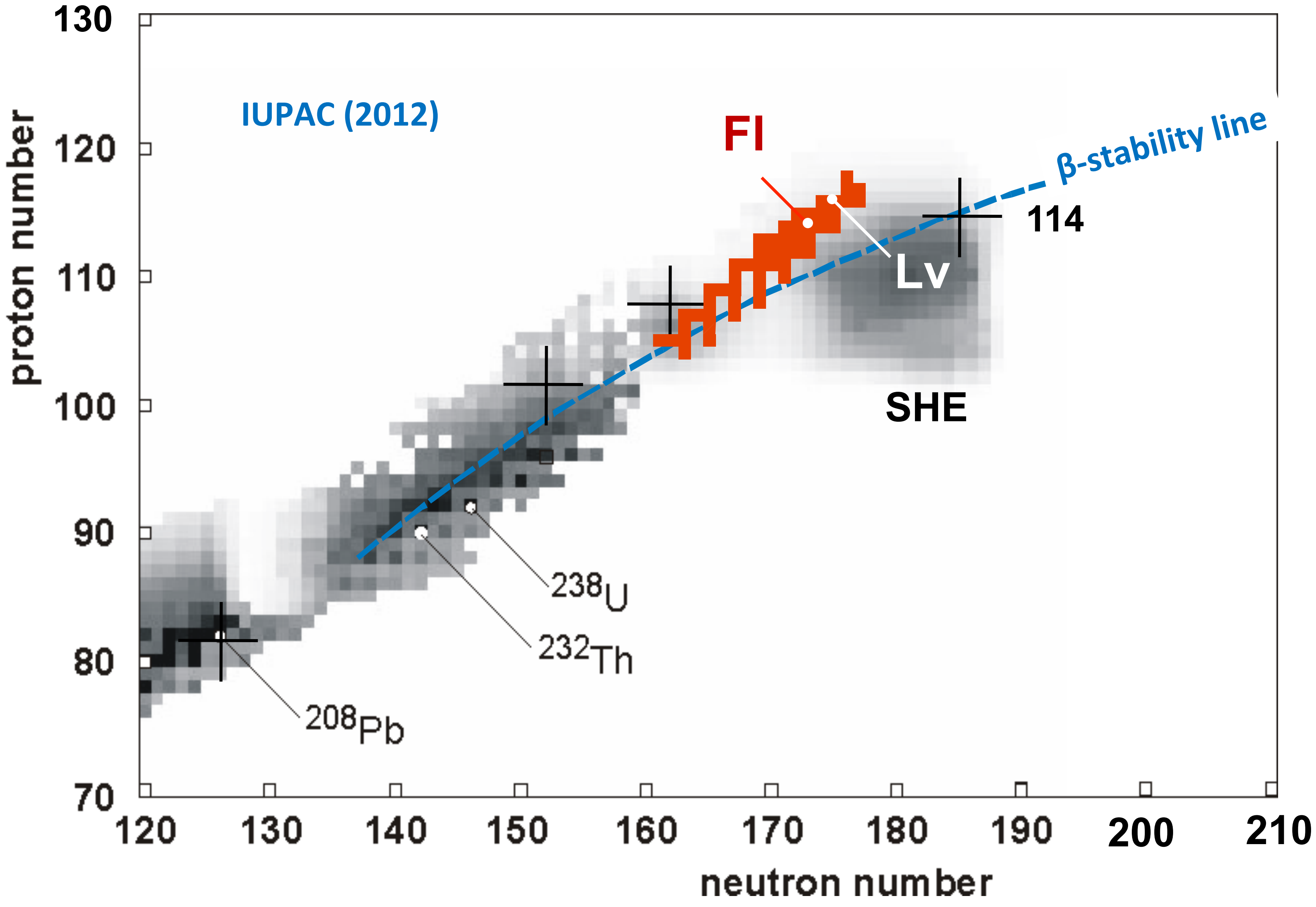
Trans-actinides

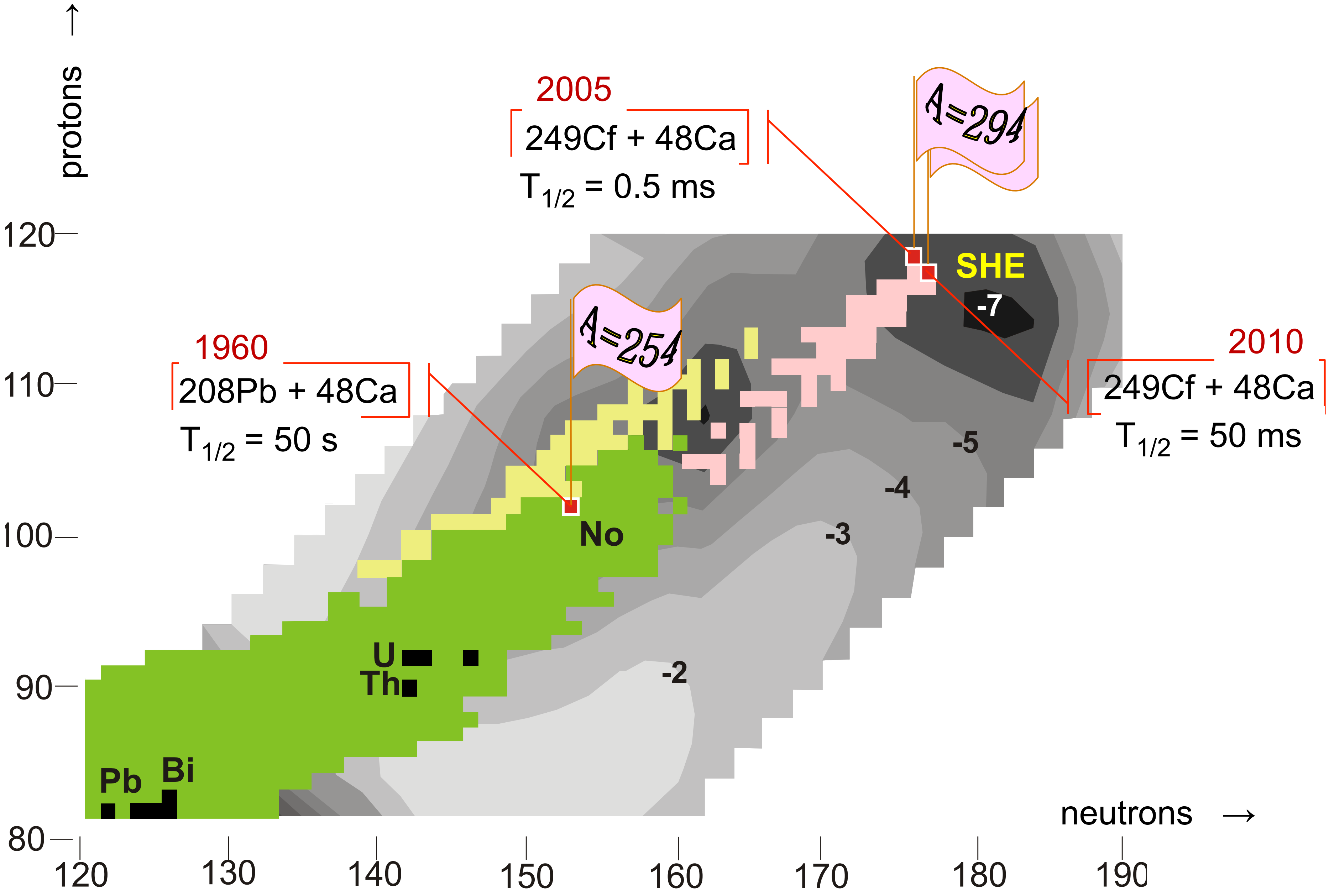
Fusion reactions of ^{208}Pb and ^{209}Bi-target nuclei with projectiles A>50

Fusion reactions of Actinide-target nuclei with ^{48}Ca projectiles

Confirmations of DGFRS data 2007 - 2014

A/Z	Setup	Laboratory	Publications
^{283}112	SHIP	GSI Darmstadt	Eur. Phys. J. A32, 251 (2007)
^{283}112	COLD	PSI-FLNR (JINR)	NATURE 447, 72 (2007)
$^{286, 287}$114	BGS	LBNL (Berkeley)	P.R. Lett. 103, 132502 (2009)
$^{288, 289}$114 $^{292, 293}$116	TASCA SHIP	GSI – Mainz GSI Darmstadt	P.R. Lett. 104, 252701 (2010) Eur. Phys. J. A48, 62 (2012)
$^{287, 288}$115 $^{293, 294}$117	TASCA TASCA	GSI – Mainz GSI – Mainz	P.R. Lett. 111, 112502 (2013) P.R. Lett. 112, 172501 (2014)
$^{292, 293}$116	GARIS	RIKEN Tokyo	Accelerator Progress Rep. (2013)


IUPAC (2012)
Fl
β-stability line
114
Lv
SHE
238U
232Th
208Pb
proton number
130
120
110
100
90
80
70
120
130
140
150
160
170
180
190
200
210
neutron number



1960

208Pb + 48Ca

$T_{1/2}$ = 50 s

2005

249Cf + 48Ca

$T_{1/2}$ = 0.5 ms

2010

249Cf + 48Ca

$T_{1/2}$ = 50 ms

With Z >40% larger than that of Bi, the heaviest stable element, we see an impressive extension in nuclear survivability.

Although SHN are at the limits of Coulomb stability,

- shell stabilization lowers ground-state energy,
- creates a fission barrier,
- and thereby enables SHN to exist.

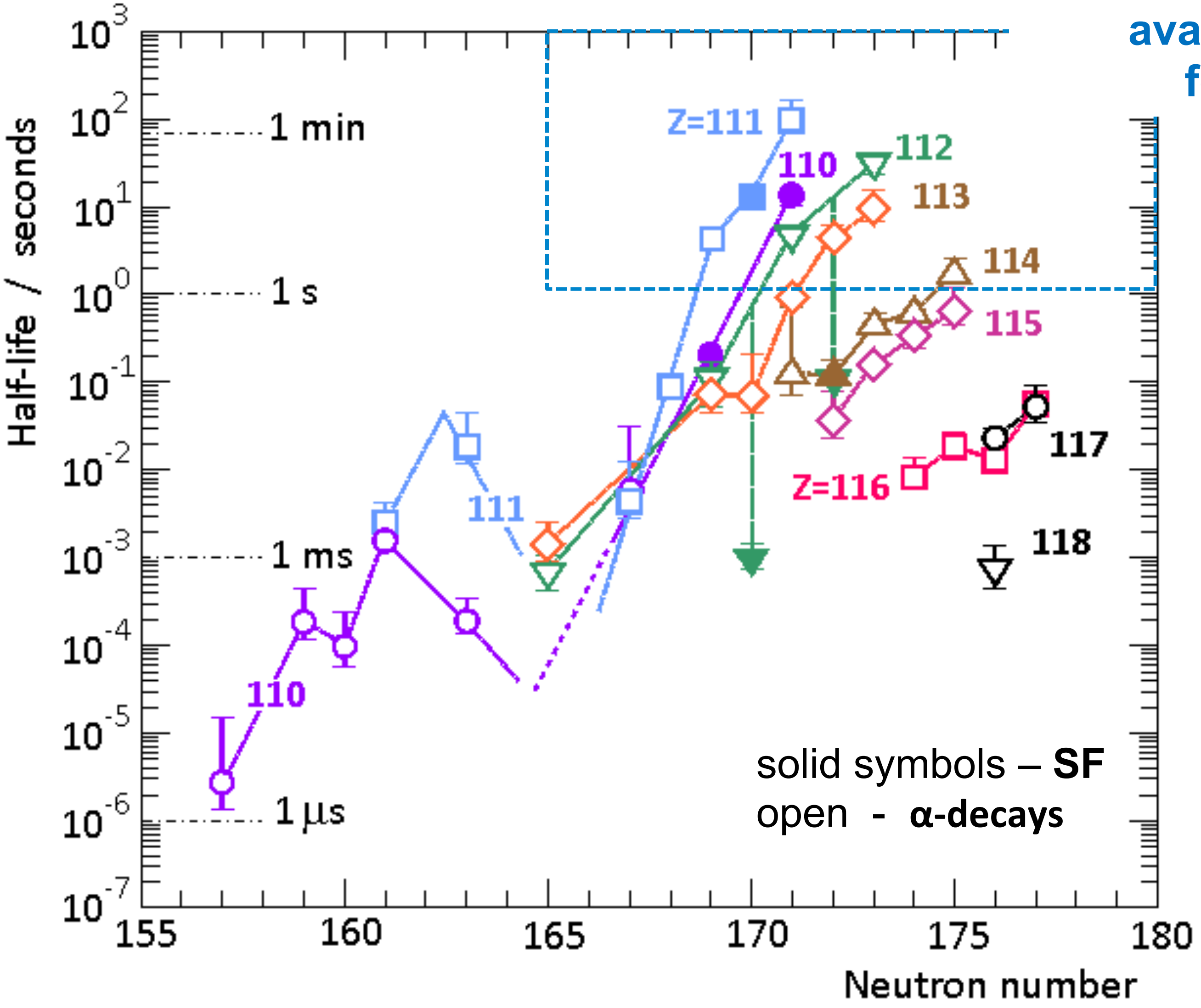
.

The fundamentals of the modern theory concerning the mass limits of nuclear matter have obtained experimental verification

Yu. Oganessian 2011

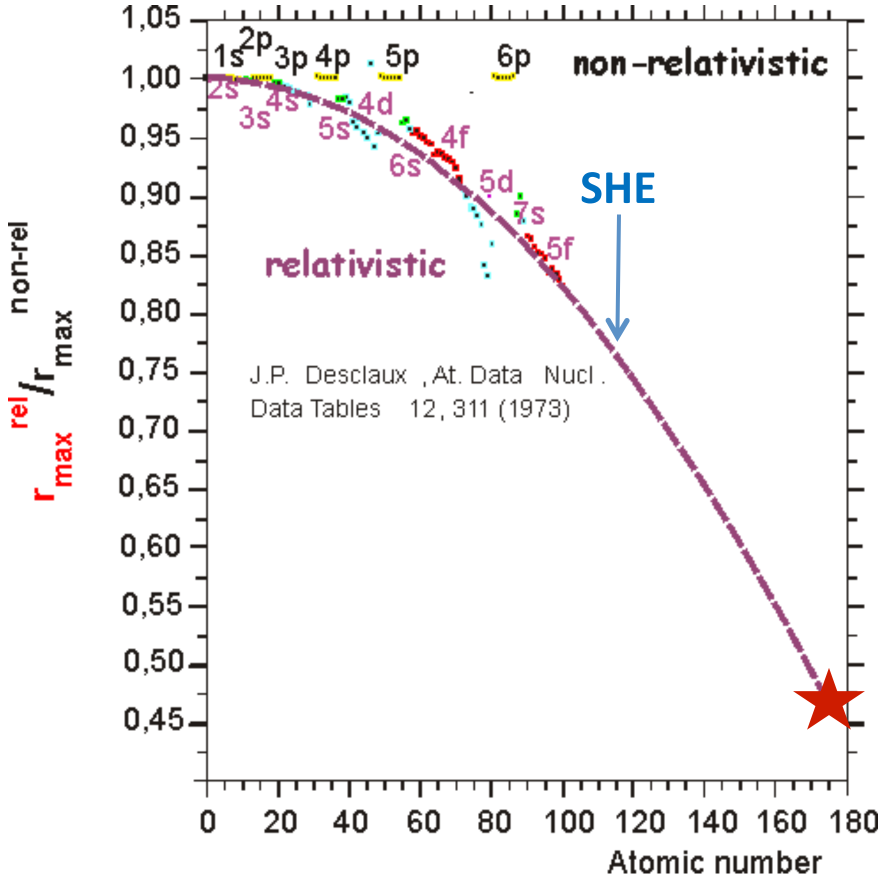
Super Heavy Atoms

Chemistry of the SHE



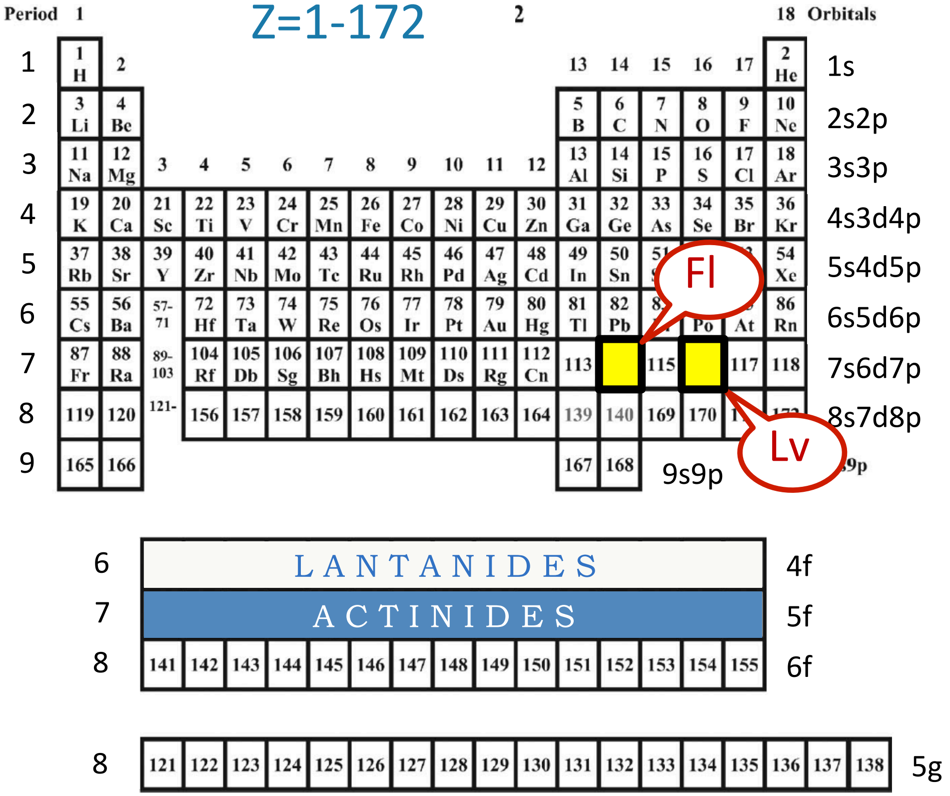
available today
for chemical
studies

Are super-heavy atoms different from lighter species?



Relativistic Contraction

Periodic Table
Z=1-172



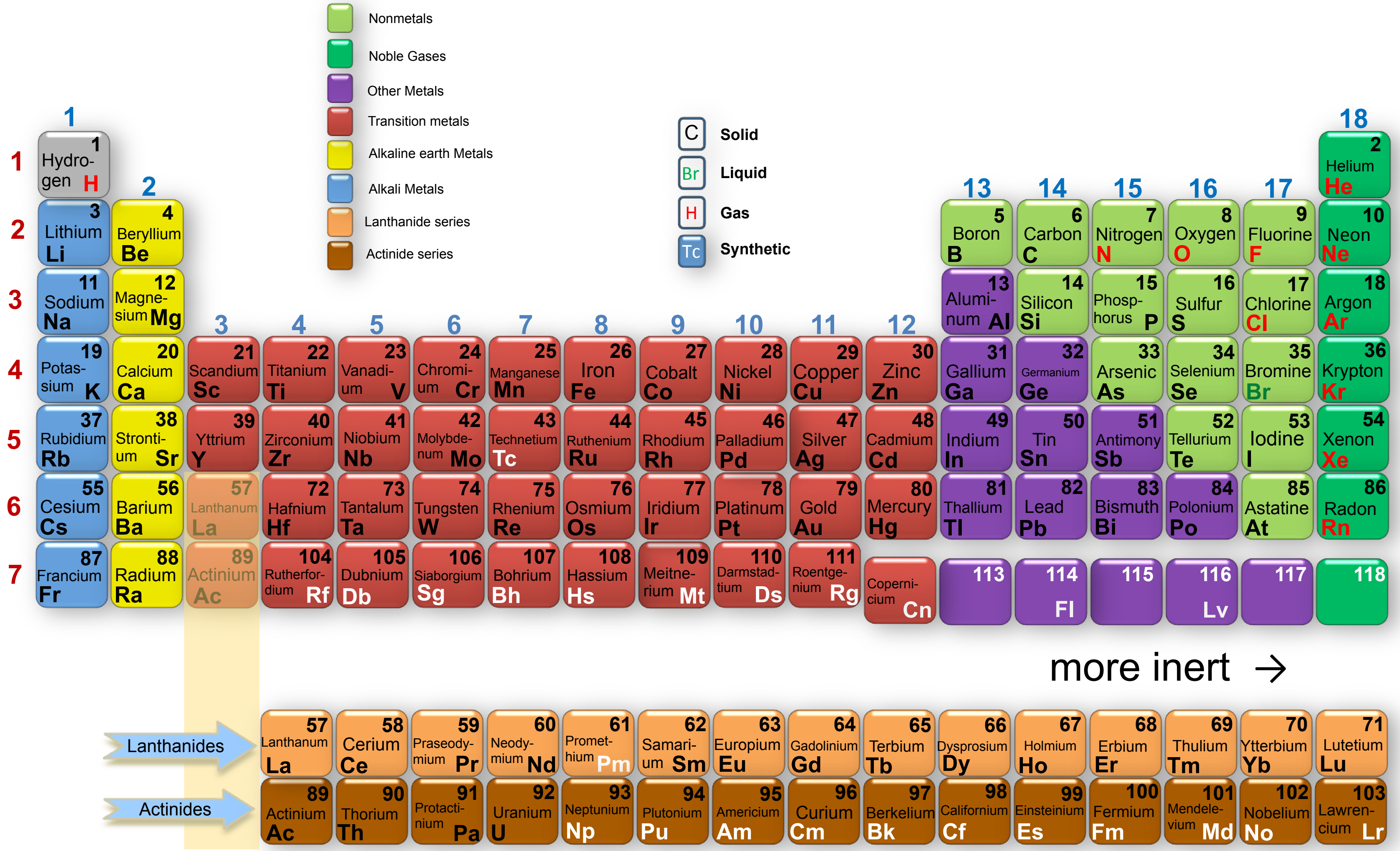
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Orbitals
1	1 H																	2 He	1s
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	2s2p
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	3s3p
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	4s3d4p
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51			54 Xe	5s4d5p
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	8	Po	At	86 Rn	6s5d6p
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113		115		117	118	7s6d7p
8	119	120	121-	156	157	158	159	160	161	162	163	164	139	140	169	170	1	17	8s7d8p
9	165	166											167	168					9s9p

6	LANTANIDES	4f
7	ACTINIDES	5f
8	141 142 143 144 145 146 147 148 149 150 151 152 153 154 155	6f
8	121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138	5g

Periodic Table based on Dirac-Fock calculations (non-relativistic)

P. Pyykkö Phys. Chem. Chem. Phys. 13, 161-168 (2011)

What are chemical properties of super-heavy elements?



🟩 Nonmetals
🟩 Noble Gases
🟪 Other Metals
🟥 Transition metals
🟨 Alkaline earth Metals
🟦 Alkali Metals
🟧 Lanthanide series
🟫 Actinide series

C **Solid**
Br **Liquid**
H **Gas**
Tc **Synthetic**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 Hydrogen H																	2 Helium He
2	3 Lithium Li	4 Beryllium Be											5 Boron B	6 Carbon C	7 Nitrogen N	8 Oxygen O	9 Fluorine F	10 Neon Ne
3	11 Sodium Na	12 Magnesium Mg											13 Aluminum Al	14 Silicon Si	15 Phosphorus P	16 Sulfur S	17 Chlorine Cl	18 Argon Ar
4	19 Potassium K	20 Calcium Ca	21 Scandium Sc	22 Titanium Ti	23 Vanadium V	24 Chromium Cr	25 Manganese Mn	26 Iron Fe	27 Cobalt Co	28 Nickel Ni	29 Copper Cu	30 Zinc Zn	31 Gallium Ga	32 Germanium Ge	33 Arsenic As	34 Selenium Se	35 Bromine Br	36 Krypton Kr
5	37 Rubidium Rb	38 Strontium Sr	39 Yttrium Y	40 Zirconium Zr	41 Niobium Nb	42 Molybdenum Mo	43 Technetium Tc	44 Ruthenium Ru	45 Rhodium Rh	46 Palladium Pd	47 Silver Ag	48 Cadmium Cd	49 Indium In	50 Tin Sn	51 Antimony Sb	52 Tellurium Te	53 Iodine I	54 Xenon Xe
6	55 Cesium Cs	56 Barium Ba	57 Lanthanum La	72 Hafnium Hf	73 Tantalum Ta	74 Tungsten W	75 Rhenium Re	76 Osmium Os	77 Iridium Ir	78 Platinum Pt	79 Gold Au	80 Mercury Hg	81 Thallium Tl	82 Lead Pb	83 Bismuth Bi	84 Polonium Po	85 Astatine At	86 Radon Rn
7	87 Francium Fr	88 Radium Ra	89 Actinium Ac	104 Rutherfordium Rf	105 Dubnium Db	106 Siaborgium Sg	107 Bohrium Bh	108 Hassium Hs	109 Meitnerium Mt	110 Darmstadtium Ds	111 Roentgenium Rg	Copernicium Cn	113	114 Fl	115	116 Lv	117	118

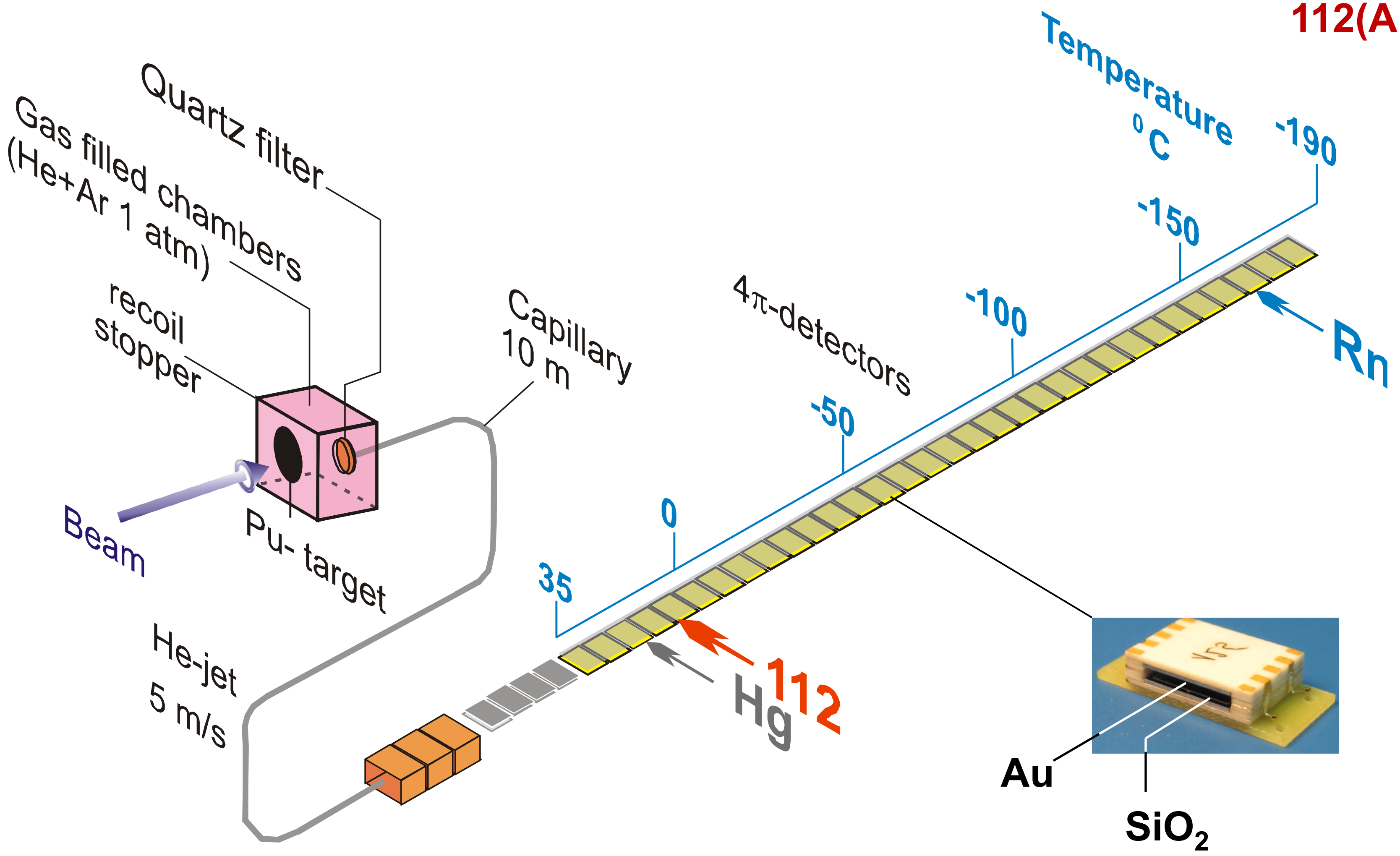
more inert →

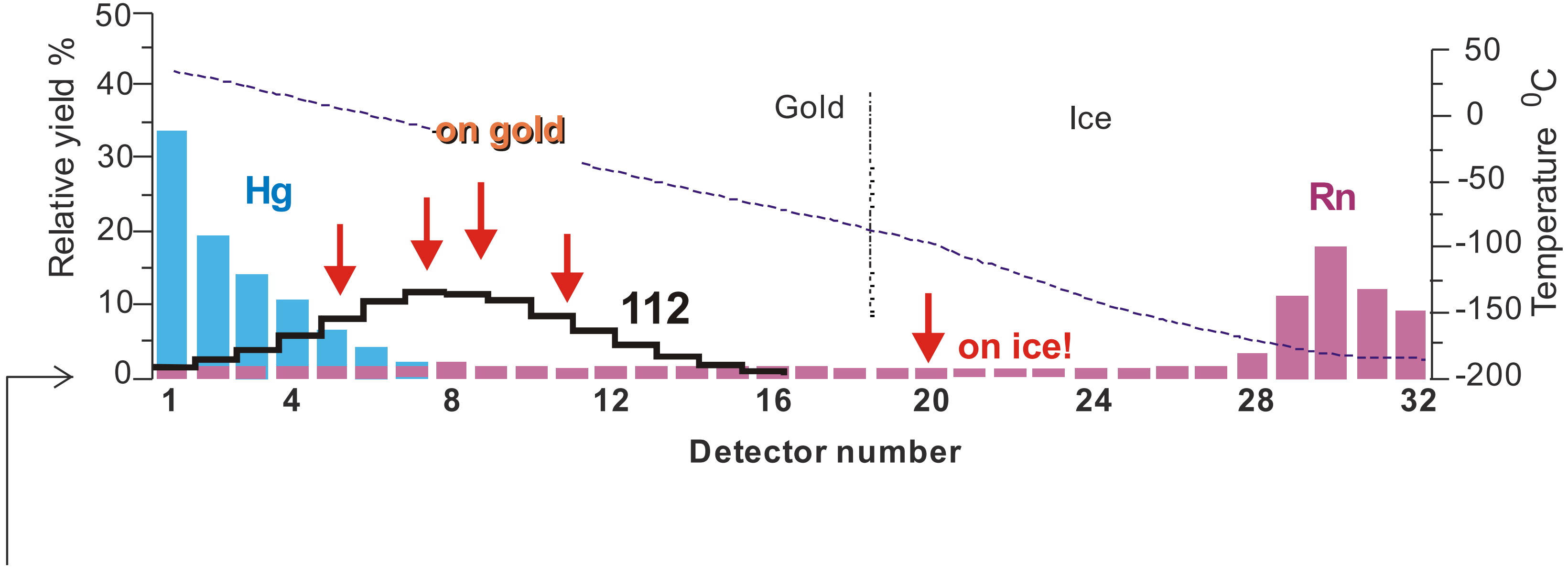
Lanthanides	57 Lanthanum La	58 Cerium Ce	59 Praseodymium Pr	60 Neodymium Nd	61 Promethium Pm	62 Samarium Sm	63 Europium Eu	64 Gadolinium Gd	65 Terbium Tb	66 Dysprosium Dy	67 Holmium Ho	68 Erbium Er	69 Thulium Tm	70 Ytterbium Yb	71 Lutetium Lu
Actinides	89 Actinium Ac	90 Thorium Th	91 Protactinium Pa	92 Uranium U	93 Neptunium Np	94 Plutonium Pu	95 Americium Am	96 Curium Cm	97 Berkelium Bk	98 Californium Cf	99 Einsteinium Es	100 Fermium Fm	101 Mendelevium Md	102 Nobelium No	103 Lawrencium Lr

R. Eichler *et al.*, Nature 447 (2007) 72

Reaction: $^{242}Pu(^{48}Ca,3n)^{287}114[0.5s] \rightarrow \alpha \rightarrow {}^{283}112[3.6s]$

Compounds:
Hg(Au)
and
112(Au)





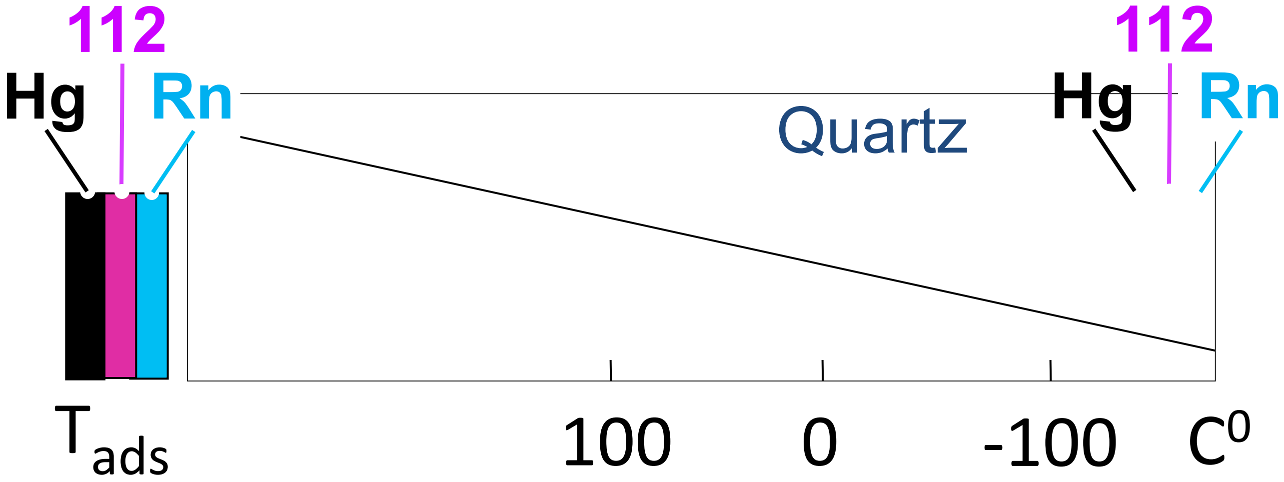
He/Ar
gas flow
+
Hg
+
Rn

T_{ads} Hg and Element Z=112 on Quartz and Gold

V. Pershina 2006

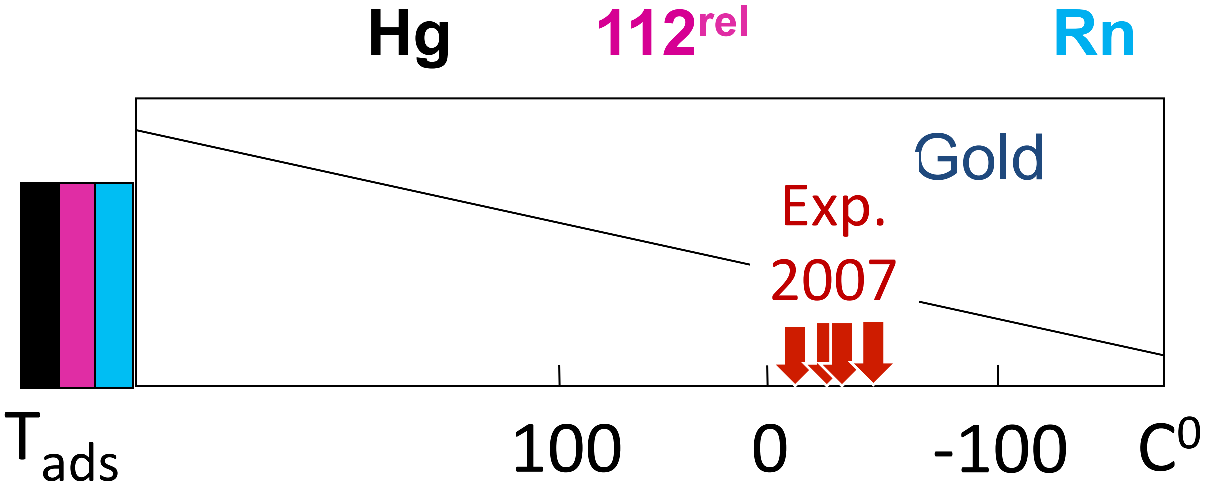
Mobil adsorption

(on quartz):

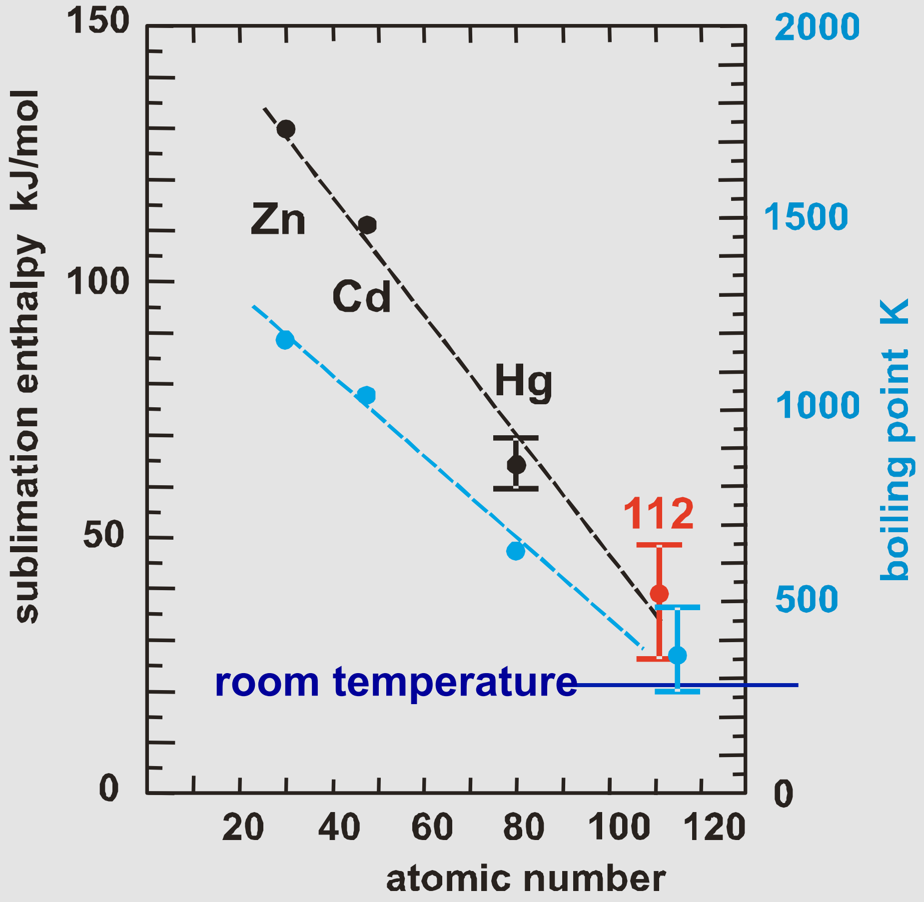


Local adsorption

(on gold):

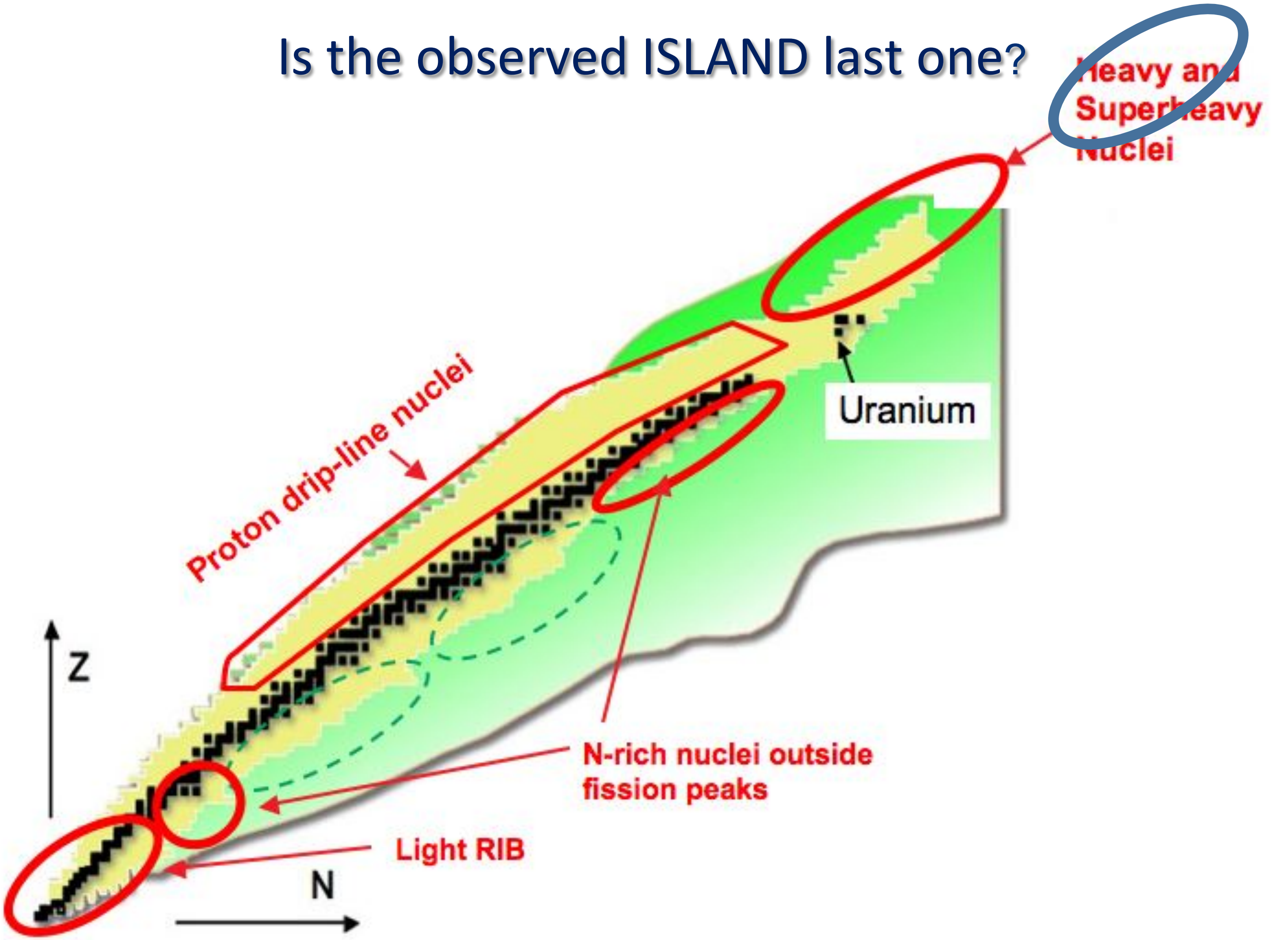


Element 112 is a noble metal – like Hg

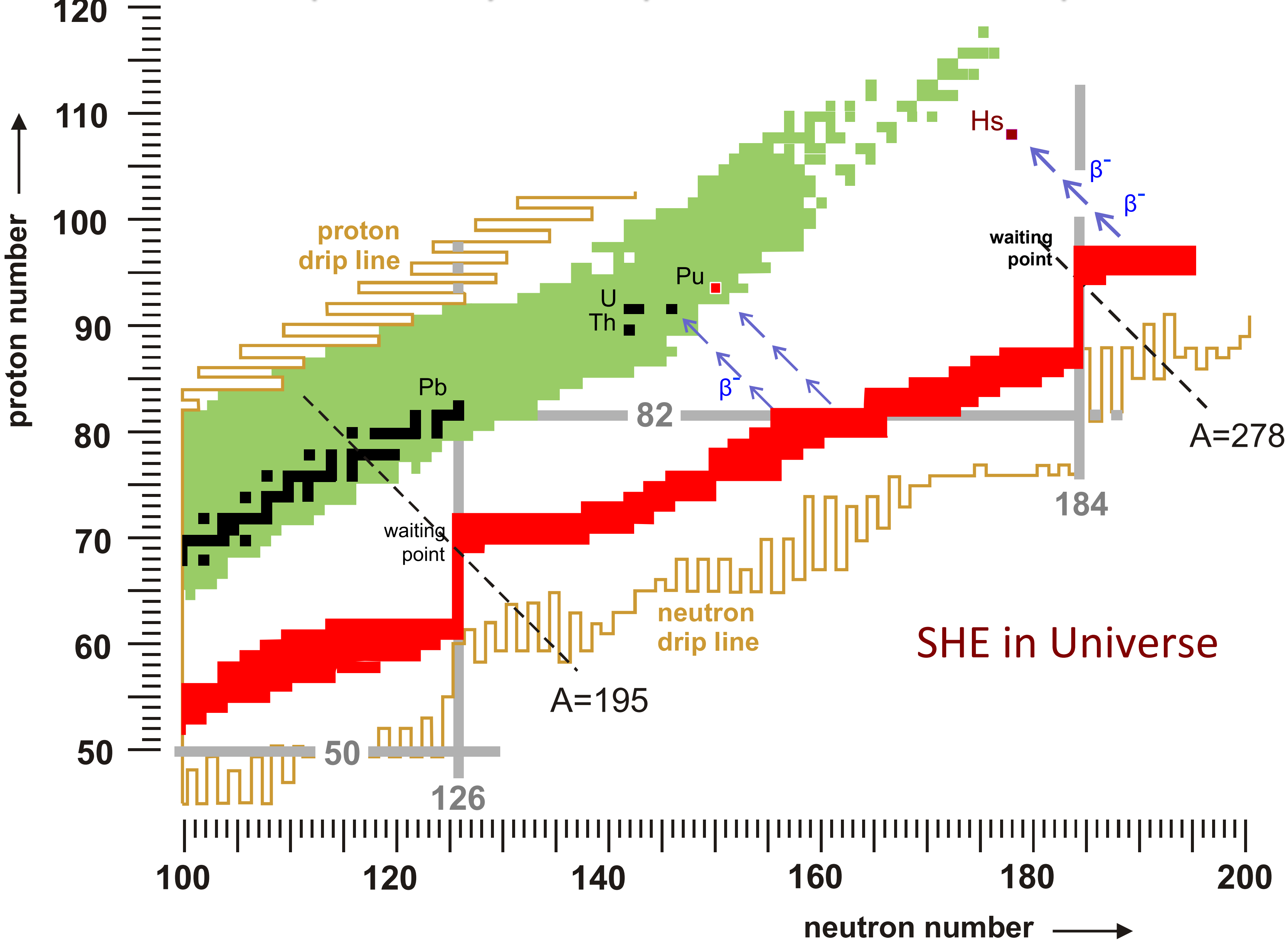


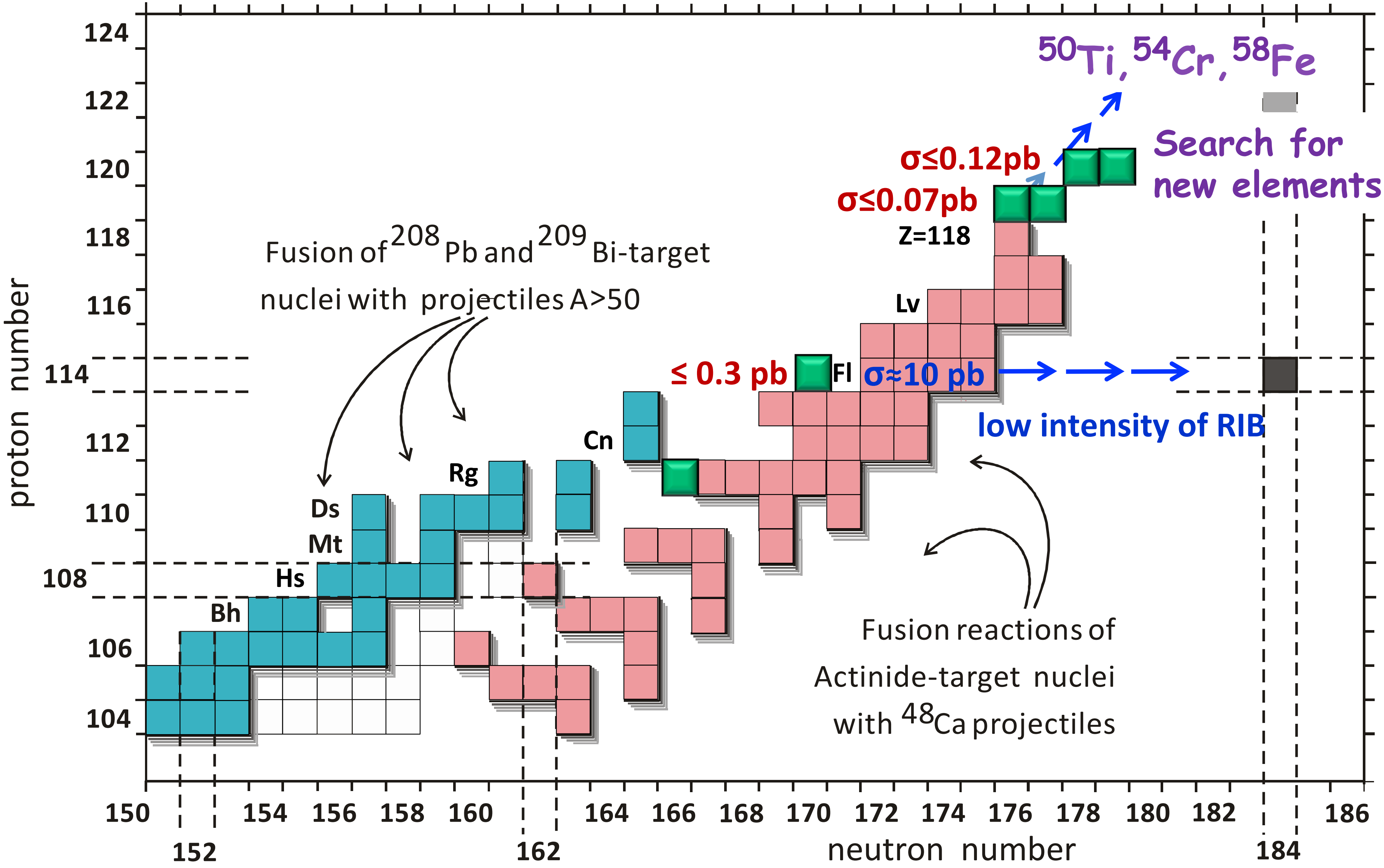
The Discovery of the SHE Raised a Questions

Is the observed ISLAND last one?



Are super-heavy nuclei produced in stellar explosions?





^{50}Ti, ^{54}Cr, ^{58}Fe
Search for new elements
σ≤0.12pb
σ≤0.07pb
Z=118
Fusion of ^{208}Pb and ^{209}Bi-target nuclei with projectiles A>50
Lv
≤ 0.3 pb
Fl
σ≈10 pb
low intensity of RIB
Cn
Rg
Ds
Mt
Hs
Bh
Fusion reactions of Actinide-target nuclei with ^{48}Ca projectiles
proton number
124
122
120
118
116
114
112
110
108
106
104
neutron number
150
152
154
156
158
160
162
164
166
168
170
172
174
176
178
180
182
184
186

obviously...

the field of the research is limited
by the production of super heavy nuclei

Everything we know about SH-nuclei produced in ^{48}Ca-induced reactions:

…allow us to think about a SHE-Factory with production rate about 100 times higher than what we currently have

SHE-Factory

Isotope production:
Cm-248
Bk-249
Cf-251

To be increased
10 times

New accelerator
High beam
dose of : Ca-48
Ti-50
Ni-64

Factor 10-20

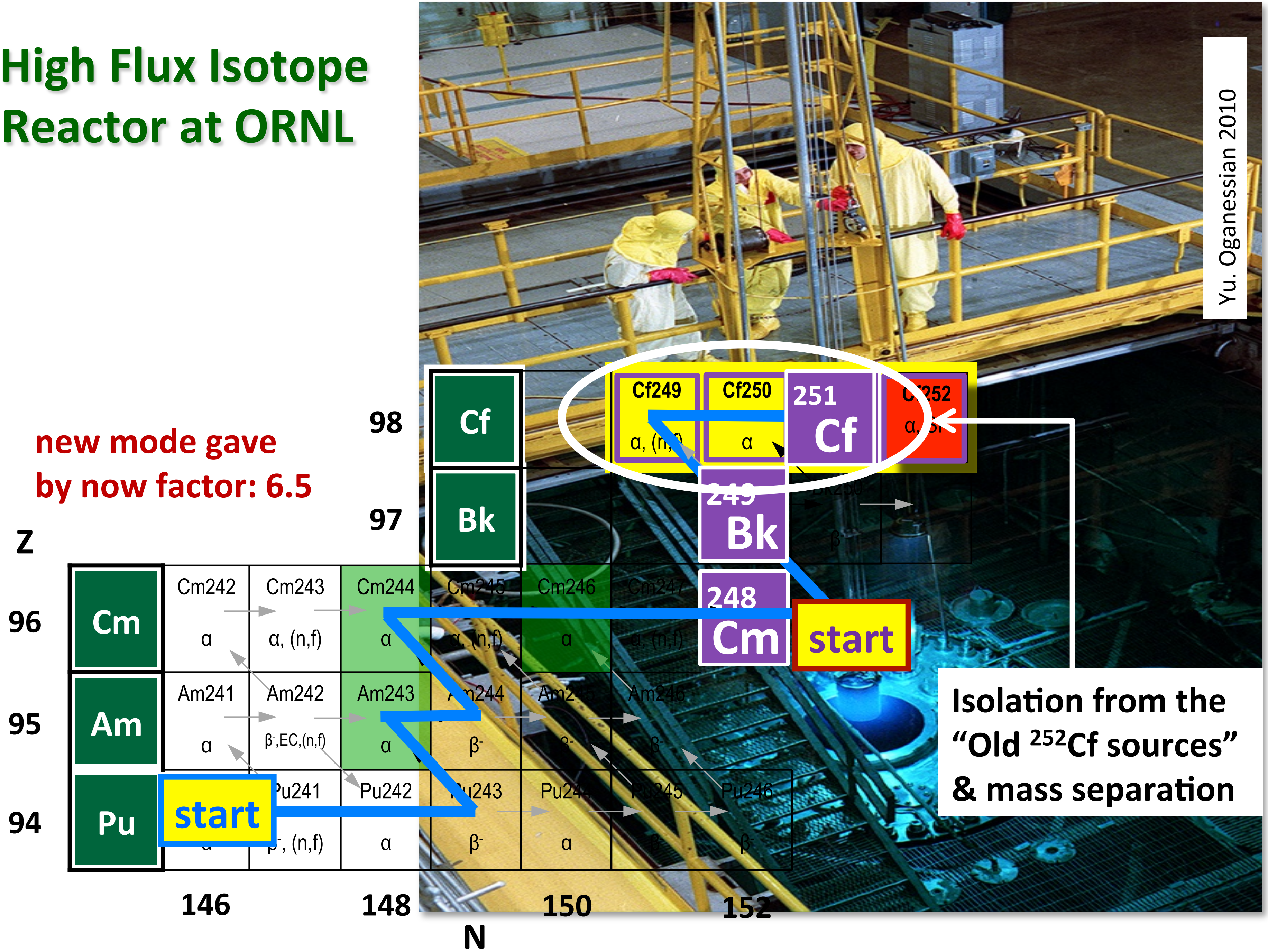
Depend of
target durability

SC- separator
& sophisticated
detectors

Factor 3-5
is closely linked
to the intellect

High Flux Isotope Reactor at ORNL

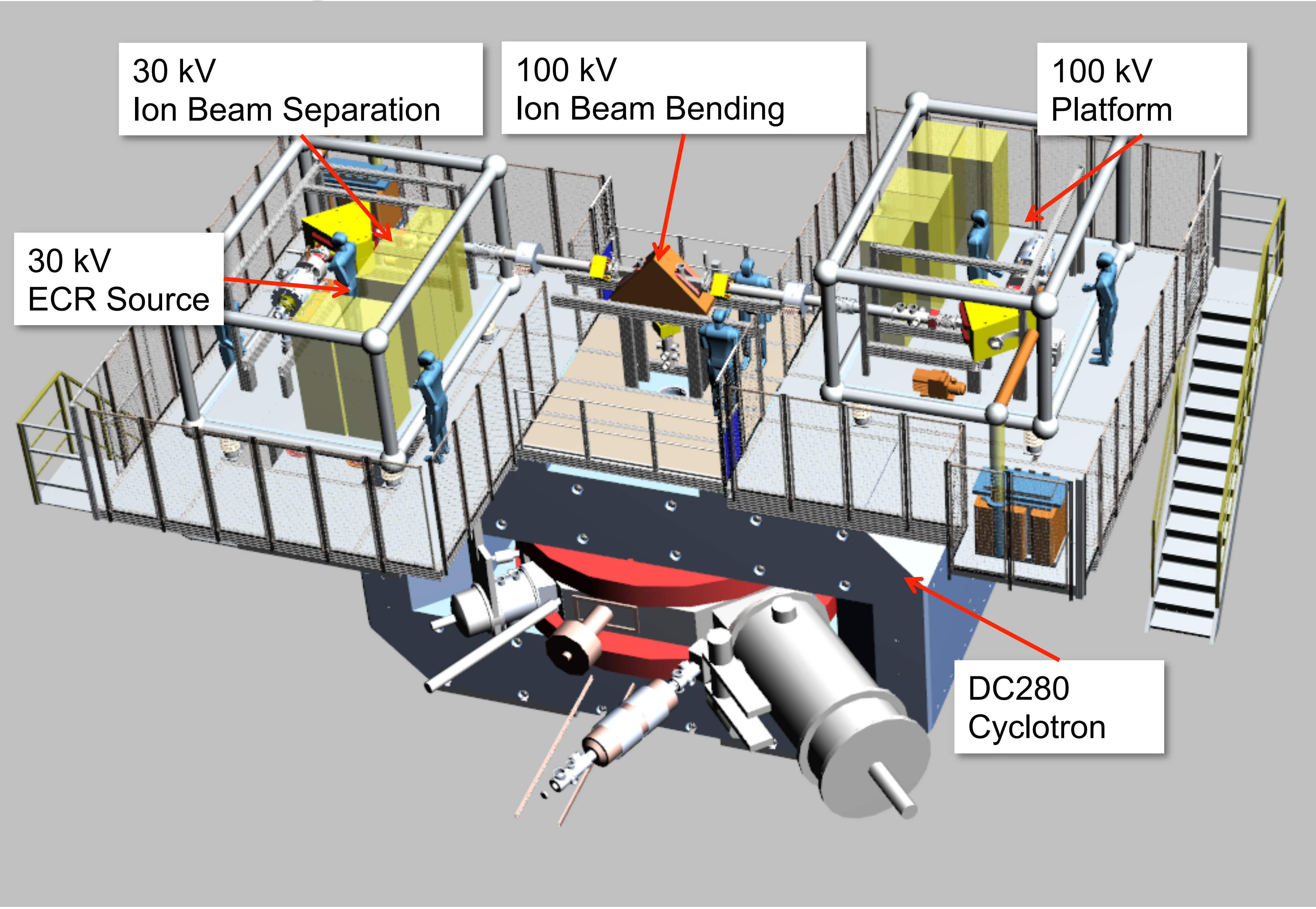
new mode gave
by now factor: 6.5



Isolation from the "Old ^{252}Cf sources" & mass separation

Yu. Oganessian 2010

DC-280 Cyclotron



30 kV
Ion Beam Separation

100 kV
Ion Beam Bending

100 kV
Platform

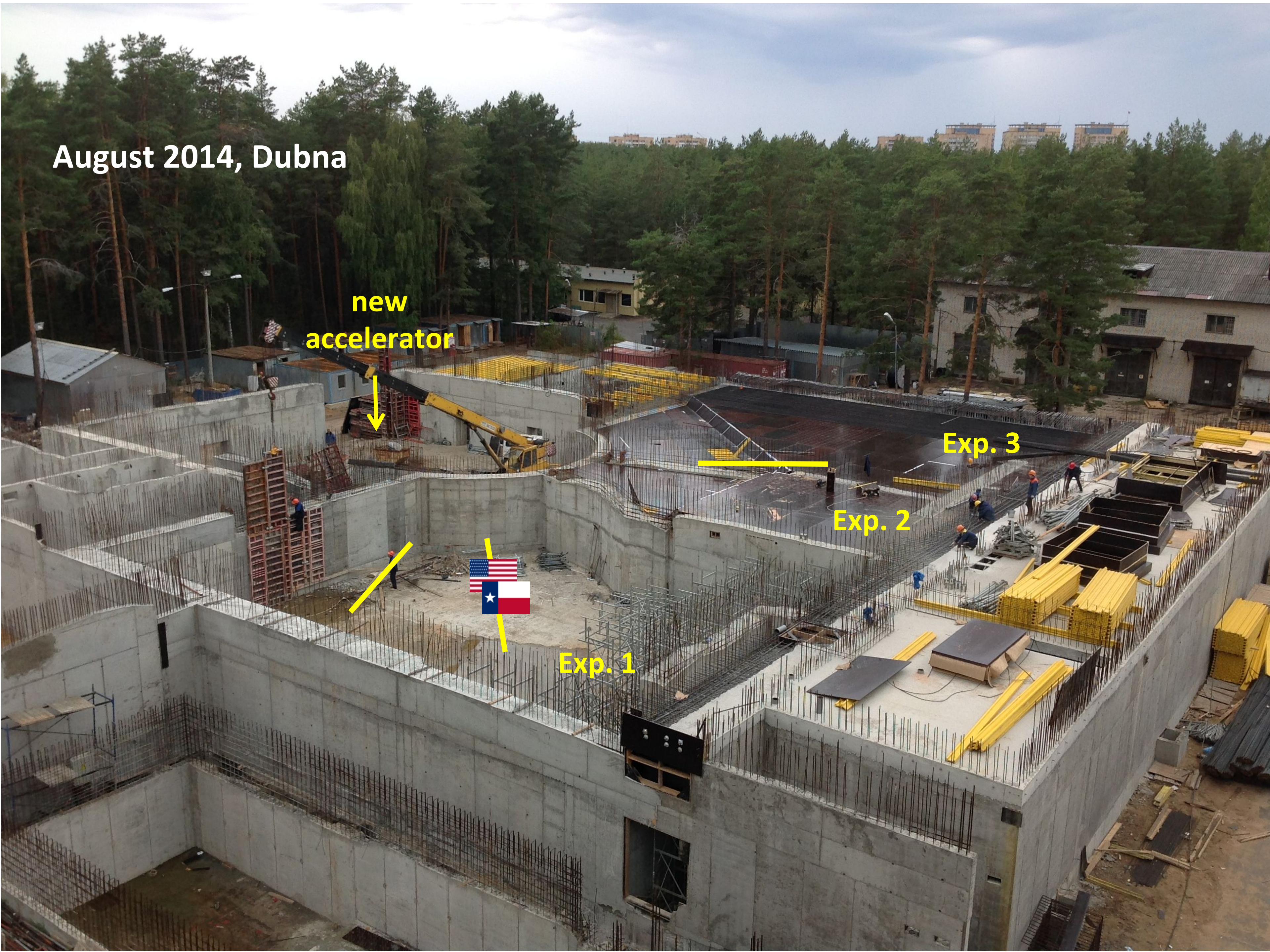
30 kV
ECR Source

DC280
Cyclotron

Projectile	Ion Charge	Intensity
^{20}Ne	$3^+ - 4^+$	$1\cdot10^{14}$ pps
^{48}Ca	$7^+ - 8^+$	**$6\cdot10^{13}$** pps
^{50}Ti	$7^+ - 9^+$	$3\cdot10^{13}$ pps
^{70}Zn	$3^+ - 4^+$	**$2\cdot10^{13}$** pps
^{86}Kr	$12^+ - 15^+$	$3\cdot10^{13}$ pps
^{100}Mo	$13^+ - 17^+$	$2\cdot10^{12}$ pps
^{124}Sn	$17^+ - 21^+$	$2\cdot10^{12}$ pps
^{136}Xe	$18^+ - 23^+$	$2\cdot10^{13}$ pps
^{208}Pb	$28^+ - 35^+$	$1\cdot10^{12}$ pps
^{238}U	$32^+ - 40^+$	$1\cdot10^{11}$ pps

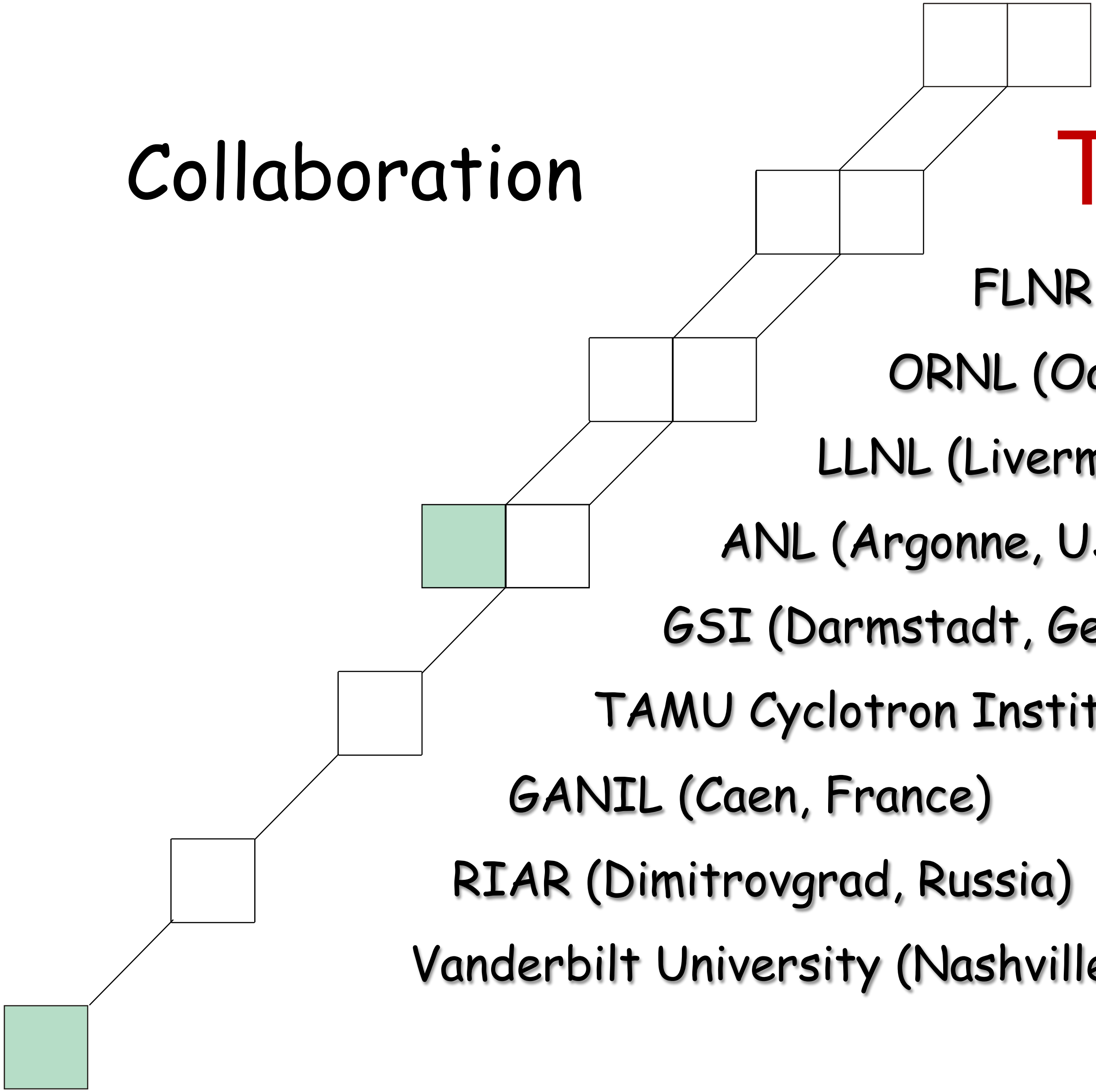
Novokramatorks
Ukraine

August 2014


August 2014, Dubna
new accelerator
Exp. 3
Exp. 2
Exp. 1

Collaboration

Thank you



FLNR, JINR (Dubna)

ORNL (Oak-Ridge, USA)

LLNL (Livermore, USA)

ANL (Argonne, USA)

GSI (Darmstadt, Germany)

TAMU Cyclotron Institute (Texas, USA)

GANIL (Caen, France)

RIAR (Dimitrovgrad, Russia)

Vanderbilt University (Nashville, USA)