The Eighth International Particle Accelerator Conference

Discovery of the Island of Stability for Super Heavy Elements

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Joint Institute for Nuclear Research

IPAC'17
May19, 2017. Copenhagen, Denmark

For more than 22 centuries

From Democritus (460 – 371 BC…)
to Dalton (1766 – 1844)

it was assumed that the objects around us are made up of tiny indivisible particles – atoms interacting with each other.

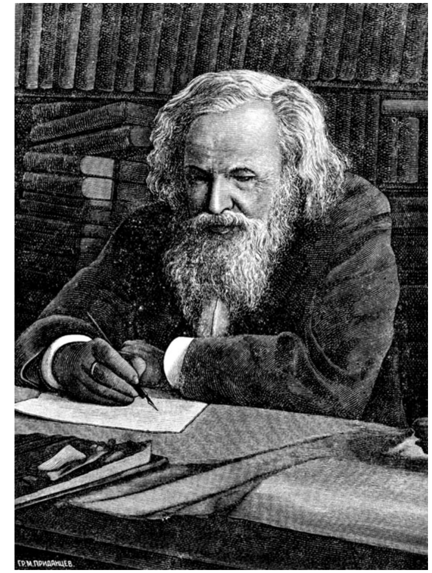
In 1808

36 elements were known only

63 elements were already know by that time

	группы элементов										
Ряды	0	I	II	III	IV	V	VI	VII		VIII	
0	Ньютоний										
1	Короний	Водород H 1,008	—	—	—	—	—	—			
2	Гелий He 4,0	Литий Li 7,03	Бериллий Be 9,1	Бор B 11,0	Углерод C 12,0	Азот N 14,01	Кислород O 16,00	Фтор F 19,0			
3	Неон Ne 19,9	Натрий Na 23,05	Магний Mg 24,36	Алюминий Al 27,1	Кремний Si 28,2	Фосфор P 31,0	Сера S 32,06	Хлор Cl 35,45			
4	Аргон Ar 38	Калий K 39,15	Кальций Ca 40,1	Скандий Sc 44,1	Титан Ti 48,1	Ванадий V 51,2	Хром Cr 52,1	Марганец Mn 55,1	Железо Fe 55,9	Кобальт Co 59	Никель Ni 59
5		Медь Cu 63,6	Цинк Zn 65,4	Галлий Ga 70,0	Германий Ge 72,5	Мышьяк As 75	Селен Se 79,2	Бром Br 79,95			
6	Криптон Kr 81,8	Рубидий Rb 85,5	Стронций Sr 87,6	Иттрий Y 89,0	Цирконий Zr 90,6	Ниобий Nb 94,0	Молибден Mo 96,0	—	Рутений Ru 101,7	Родий Rh 103,0	Палладий Pd 106,5
7		Серебро Ag 107,93	Кадмий Cd 112,4	Индий In 115,0	Олово Sn 119,0	Сурьма Sb 120,2	Теллур Te 127	Иод I 127			
8	Ксенон Xe 128	Цезий Cs 132,9	Барий Ba 137,4	Лантан La 138,9	Церий Ce 140,2	—	—	—	—	—	—
9		—	—	—	—	—	—	—			
10	—	—	—	Иттербий Yb 173	—	Тантал Ta 183	Вольфрам W 184	—	Осмий Os 191	Иридий Ir 193	Платина Pt 194,8
11											
12	—	—	Радий Ra 225	—	Торий Th 232,5	—	Уран U 238,5				

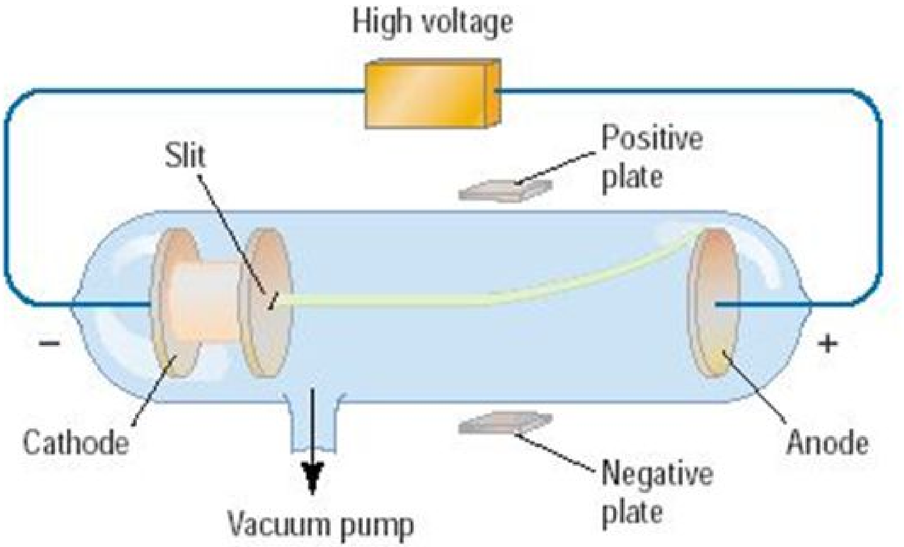
Genuine D.I.Mendeleev's Table

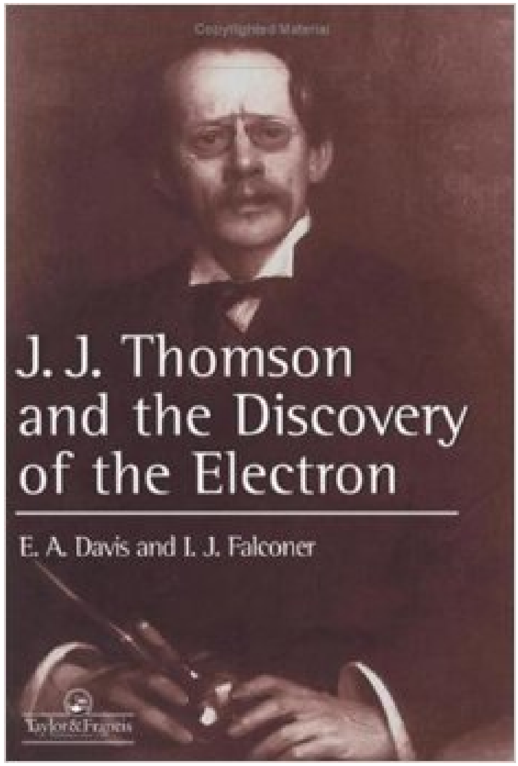


Dmitri Mendeleev
1869

Discovery of the Electron

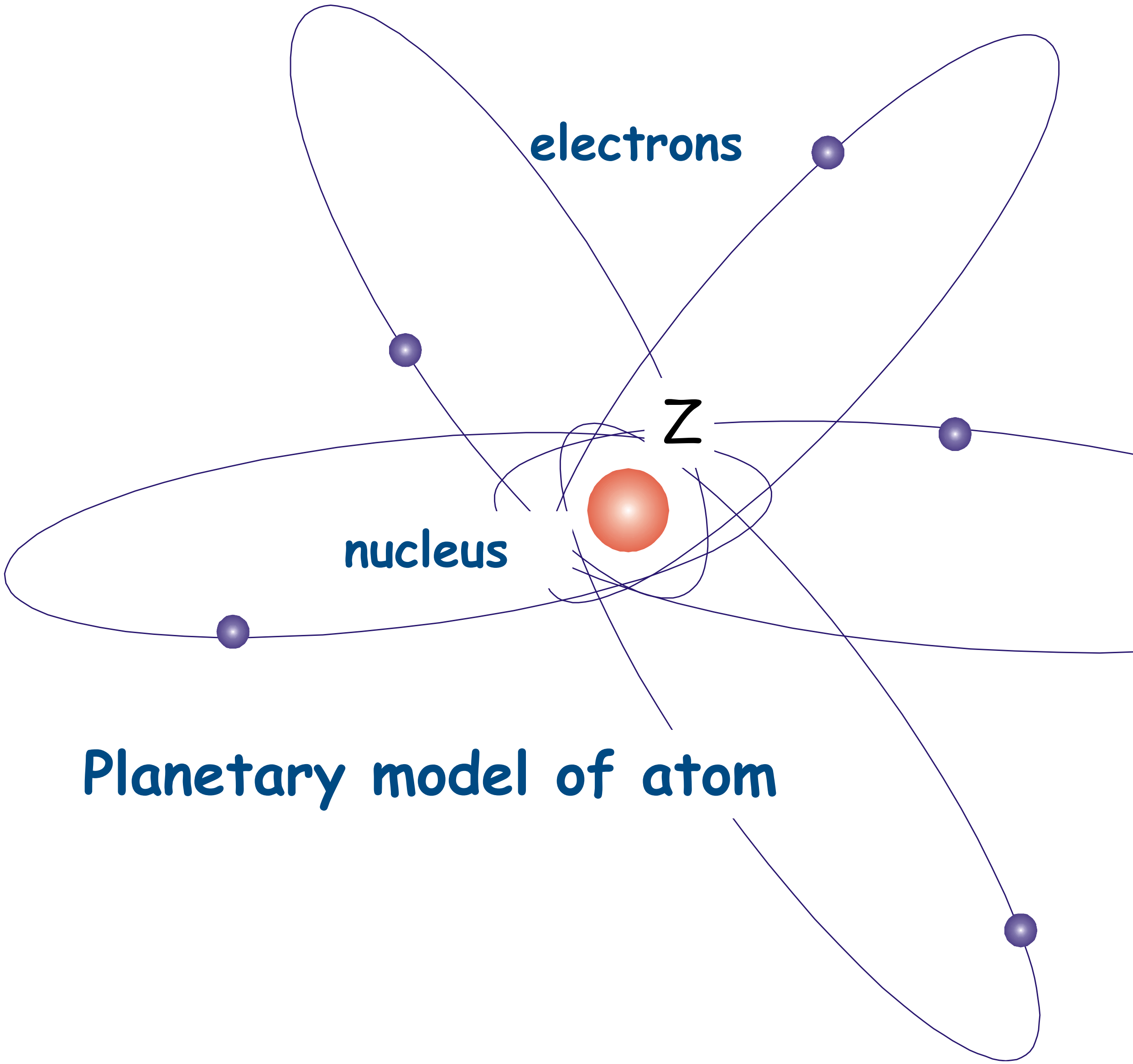
In 1897, J.J. Thomson used a cathode ray tube to deduce the presence of a negatively charged particle.



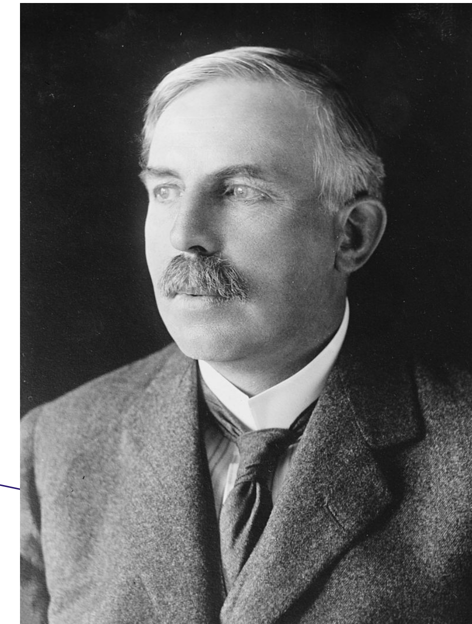


Cathode ray tubes pass electricity through a gas that is contained at a very low pressure.

86 elements were already known by that time



Planetary model of atom



Ernest Rutherford
March7, 1911

In attempts to describe the properties of nuclear matter, George Gamow made a daring assumption that atomic nucleus may be similar to a drop of positively charged liquid.

George Gamow 1928

In fact, the density of nuclear liquid is 10^{15} times more than that of water

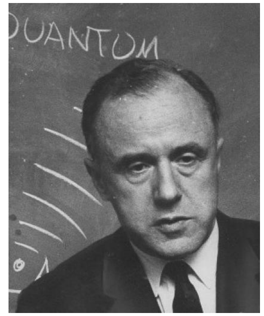
Charged Liquid Drop Model
of the atomic nucleus.

G. Gamow, 1928.

We will be discussing today the problem of synthesis and properties of extremely heavy nuclei to get answers to questions about:

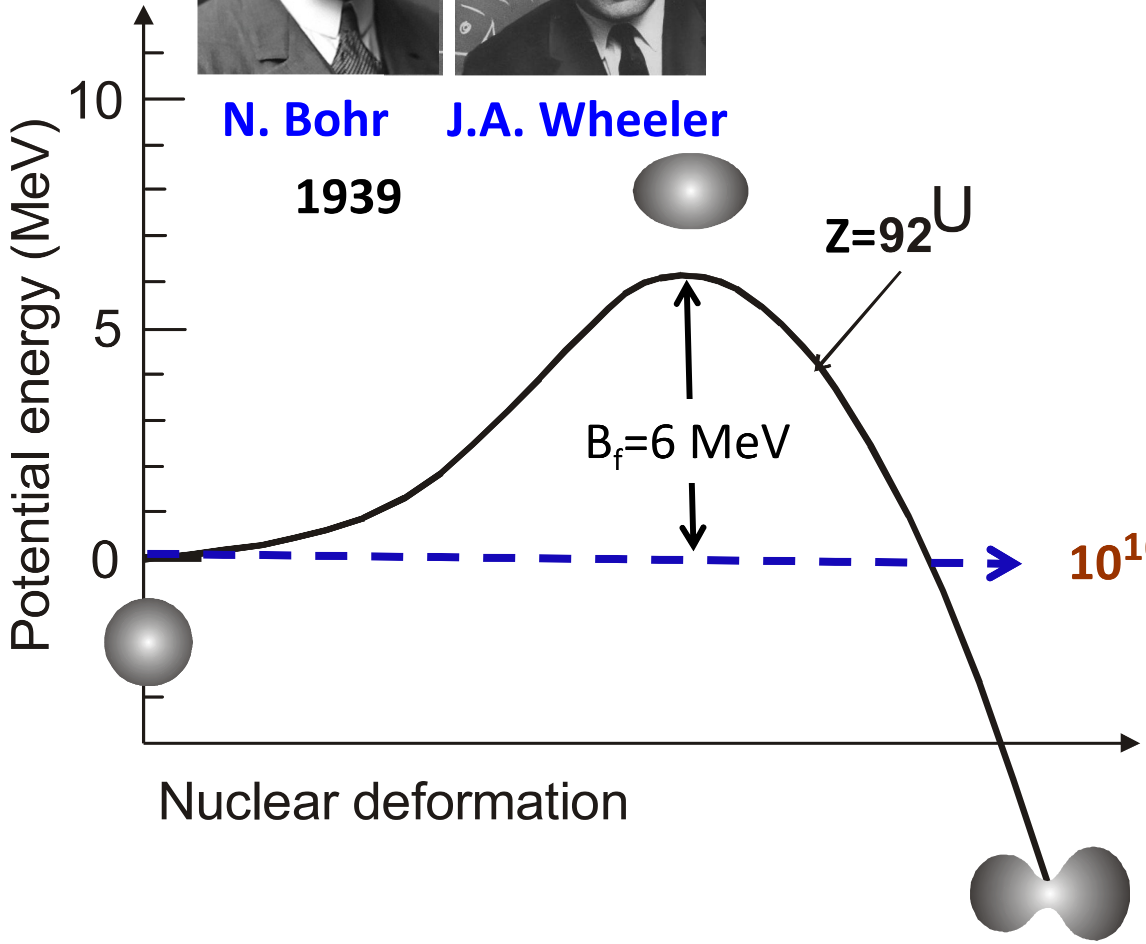
- **How big the nuclei can be?**
- **What of proton and neutron number they may have?**
- **Where is the mass limit of the nuclei?**
- **How many chemical elements can be and what are their properties?**

Nuclear fission

N. Bohr J.A. Wheeler

1939



10^{16} years (exp.)

G.N. Flerov

1940

K.A. Petrzhak

Nuclear fission

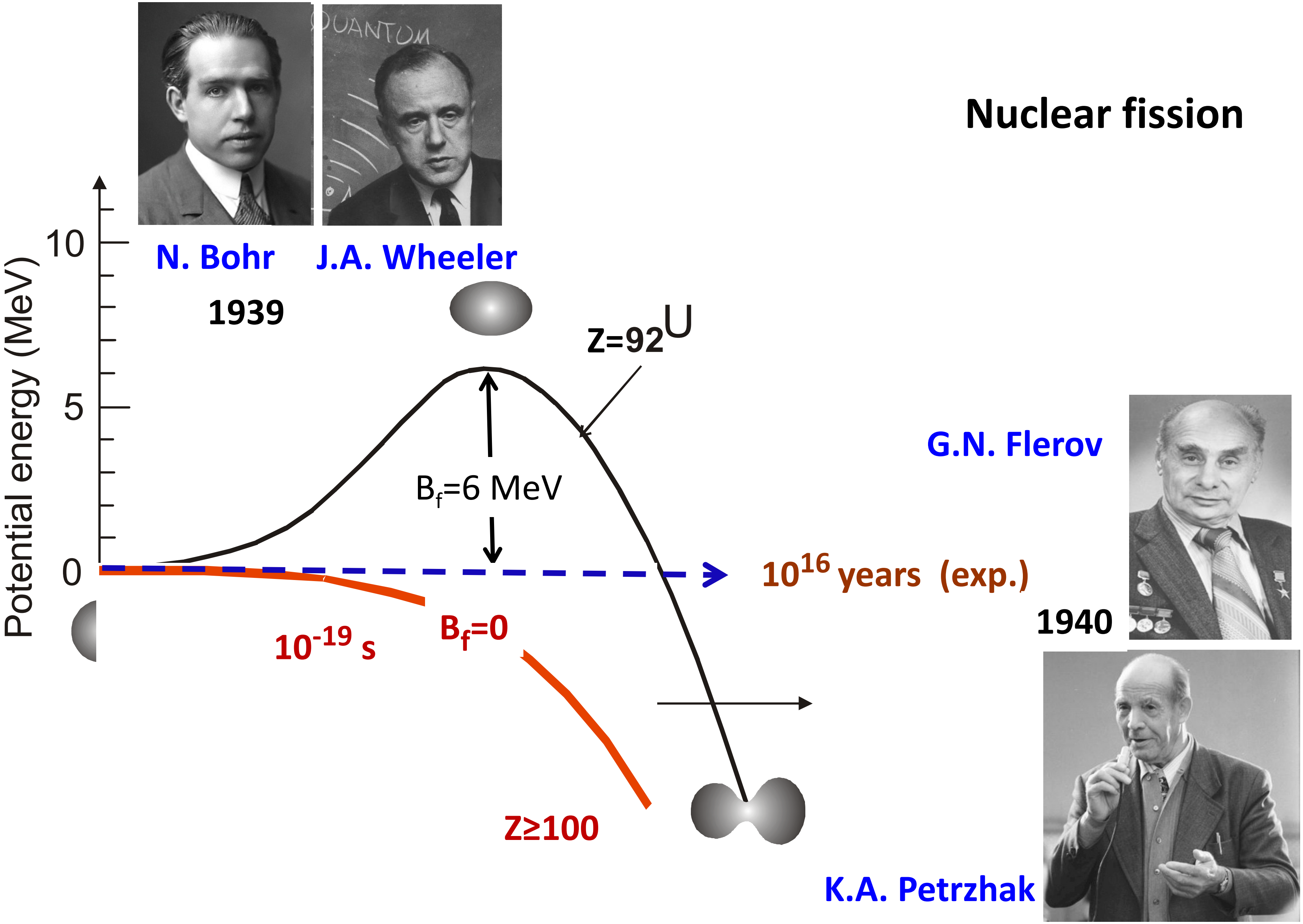
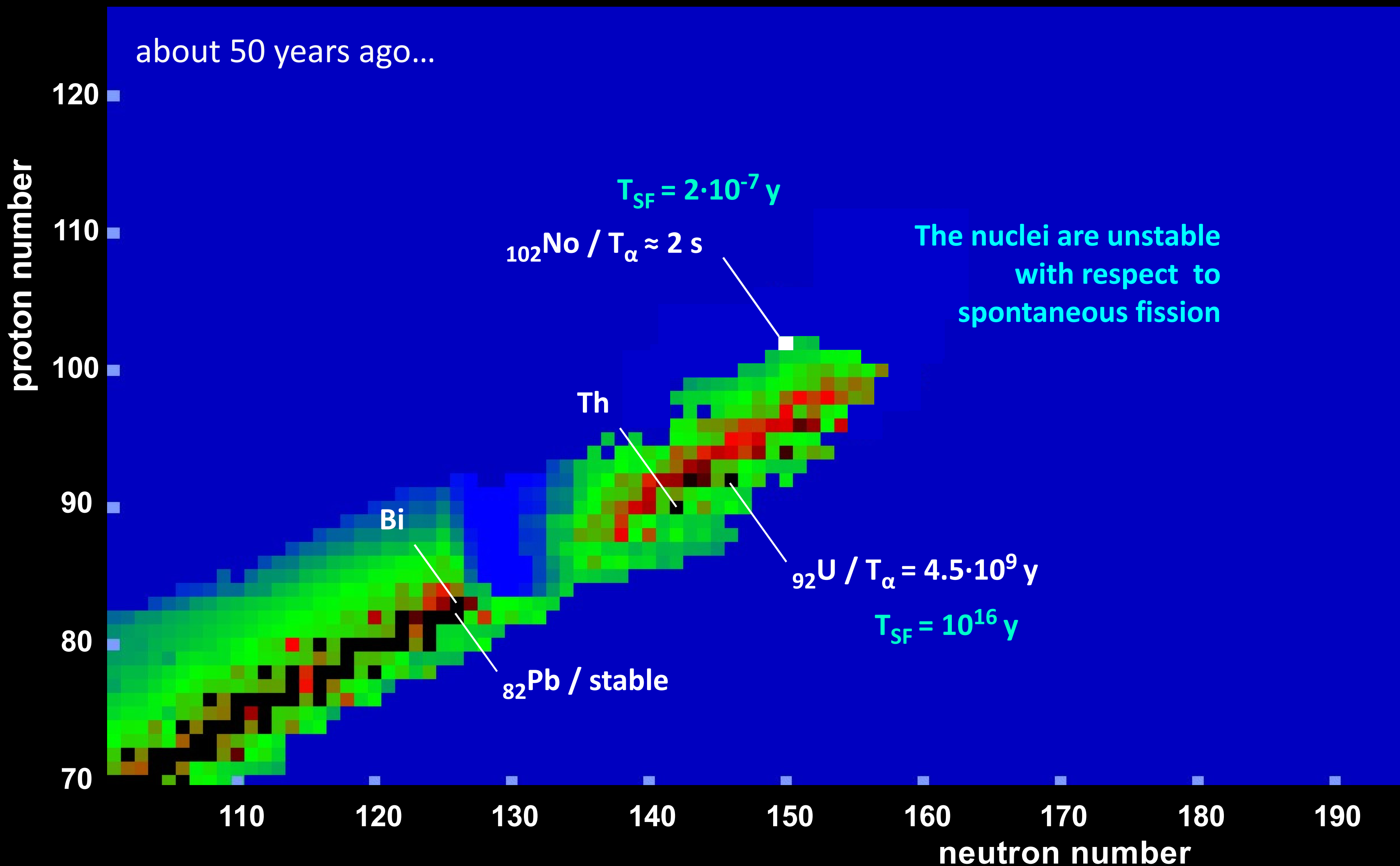
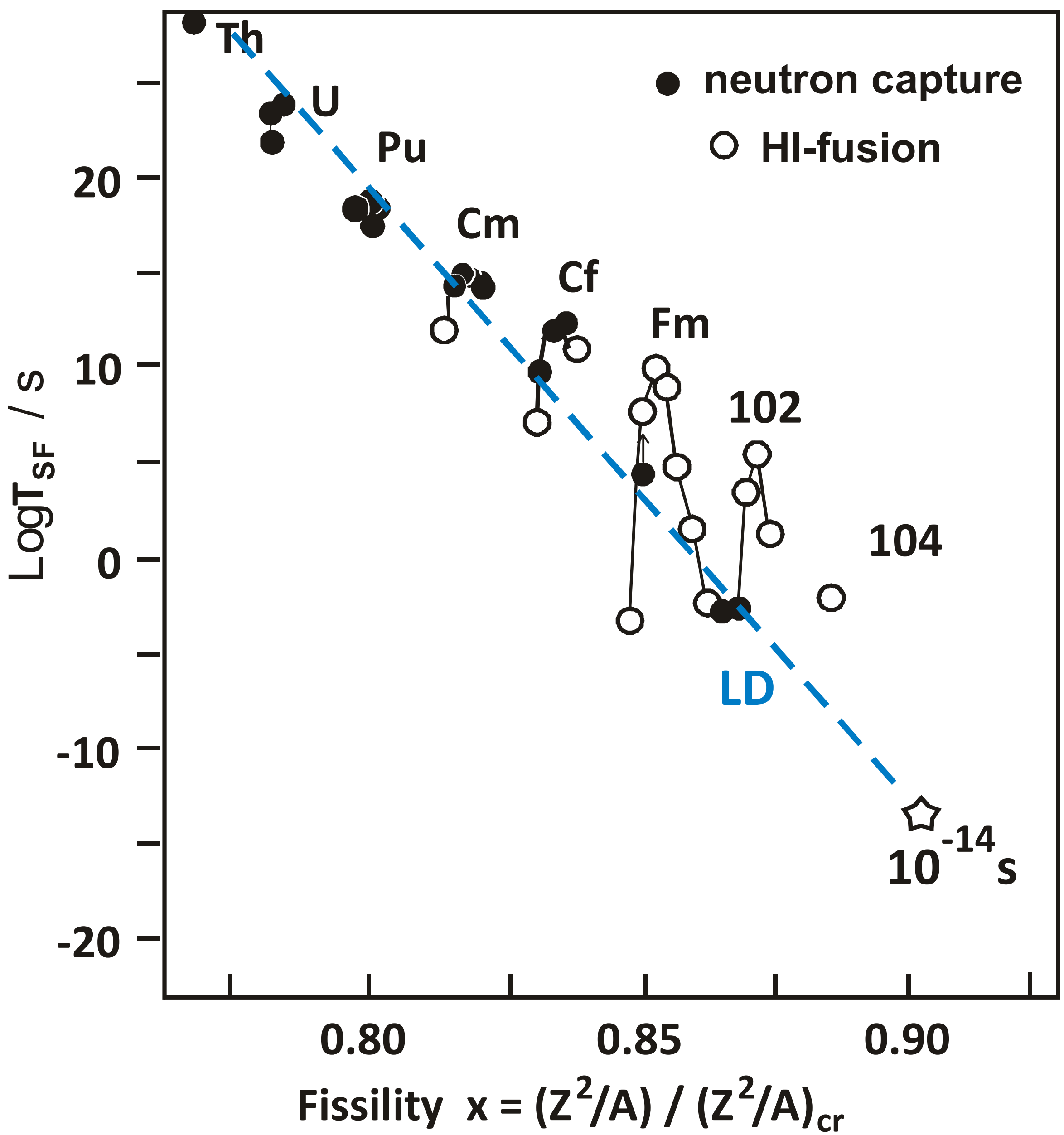


Chart of nuclides

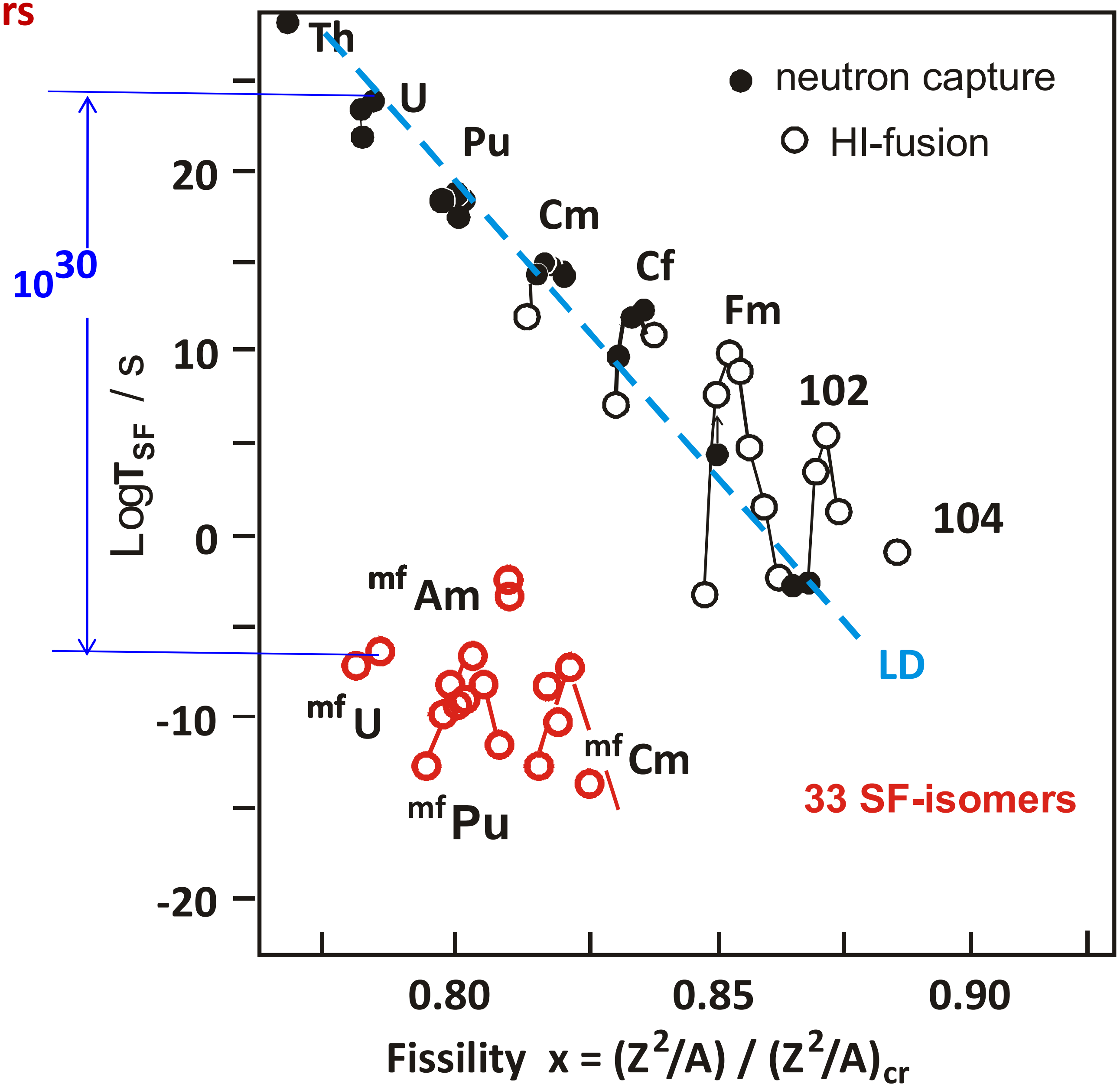
Macroscopic theory (Liquid Drop Model)





neutron capture
HI-fusion
Th
U
Pu
Cm
Cf
Fm
102
104
LD
10^-14 s
20
10
0
-10
-20
LogT_SF / s
0.80
0.85
0.90
Fissility x = (Z^2/A) / (Z^2/A)_cr

Discovery SF isomers
JINR, Dubna, 1962



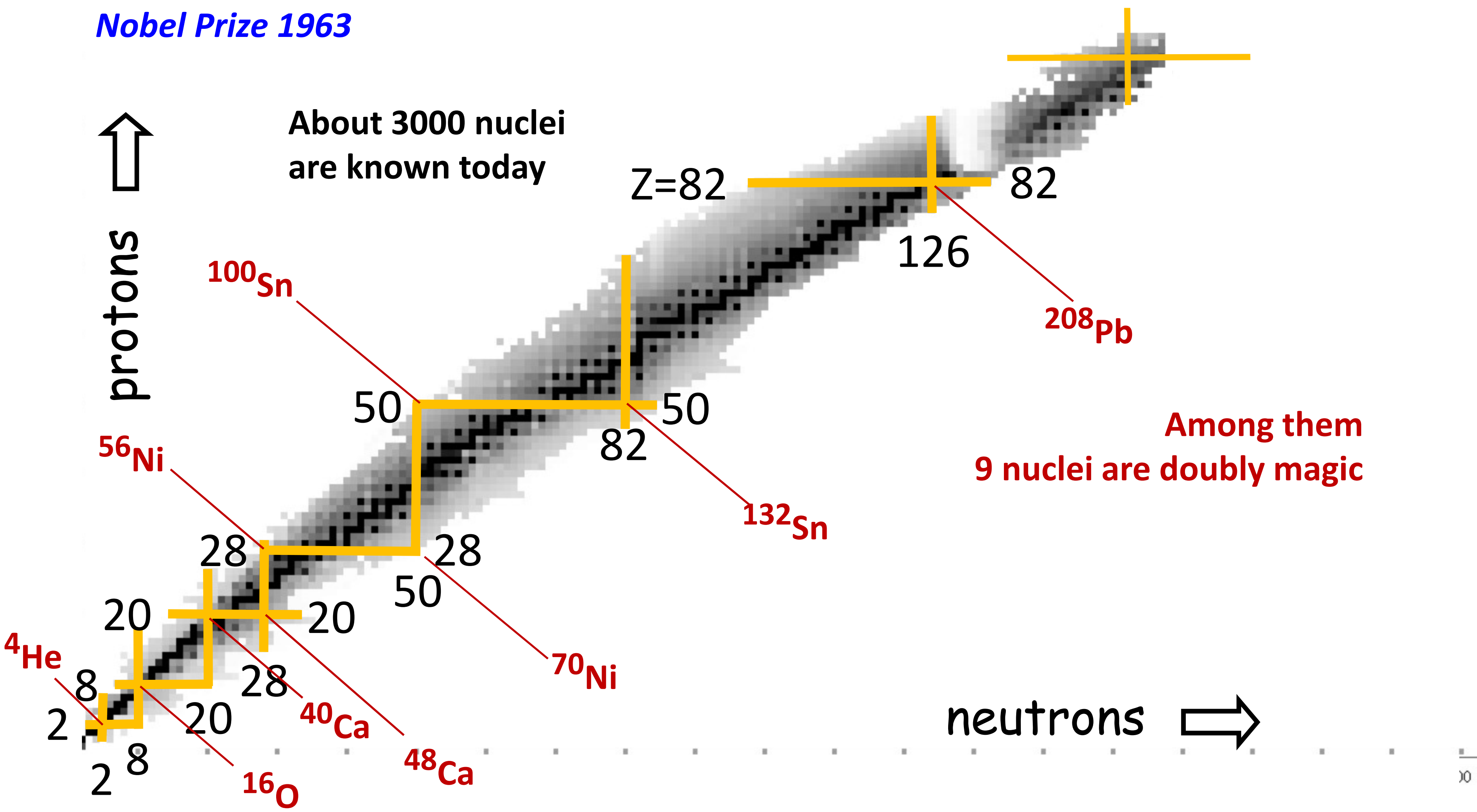
Shell and magic numbers

E. Wigner/ M. Goeppert-Mayer /H. Jensen
Nobel Prize 1963

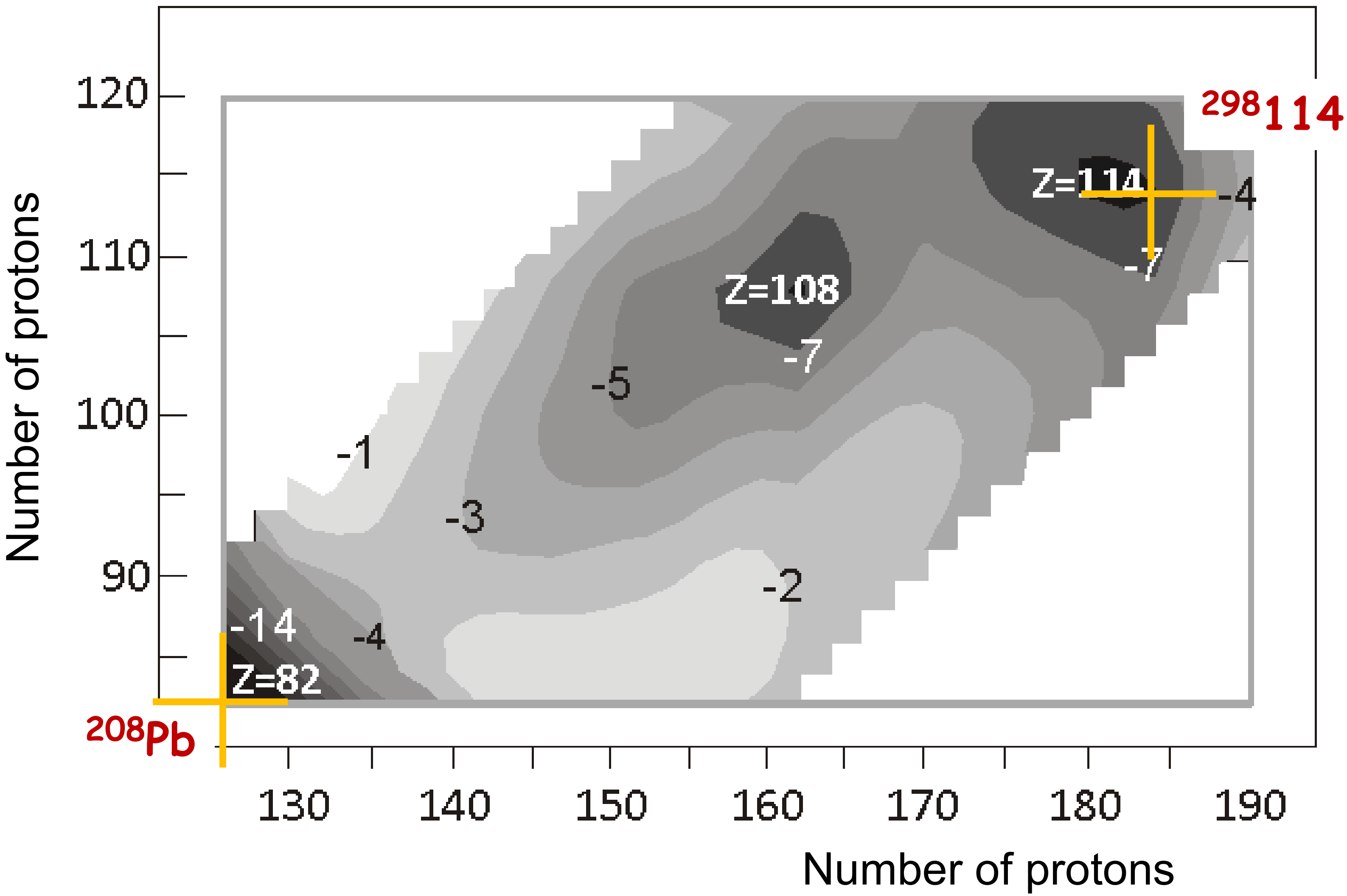
NEW SHELLS ?

About 3000 nuclei are known today

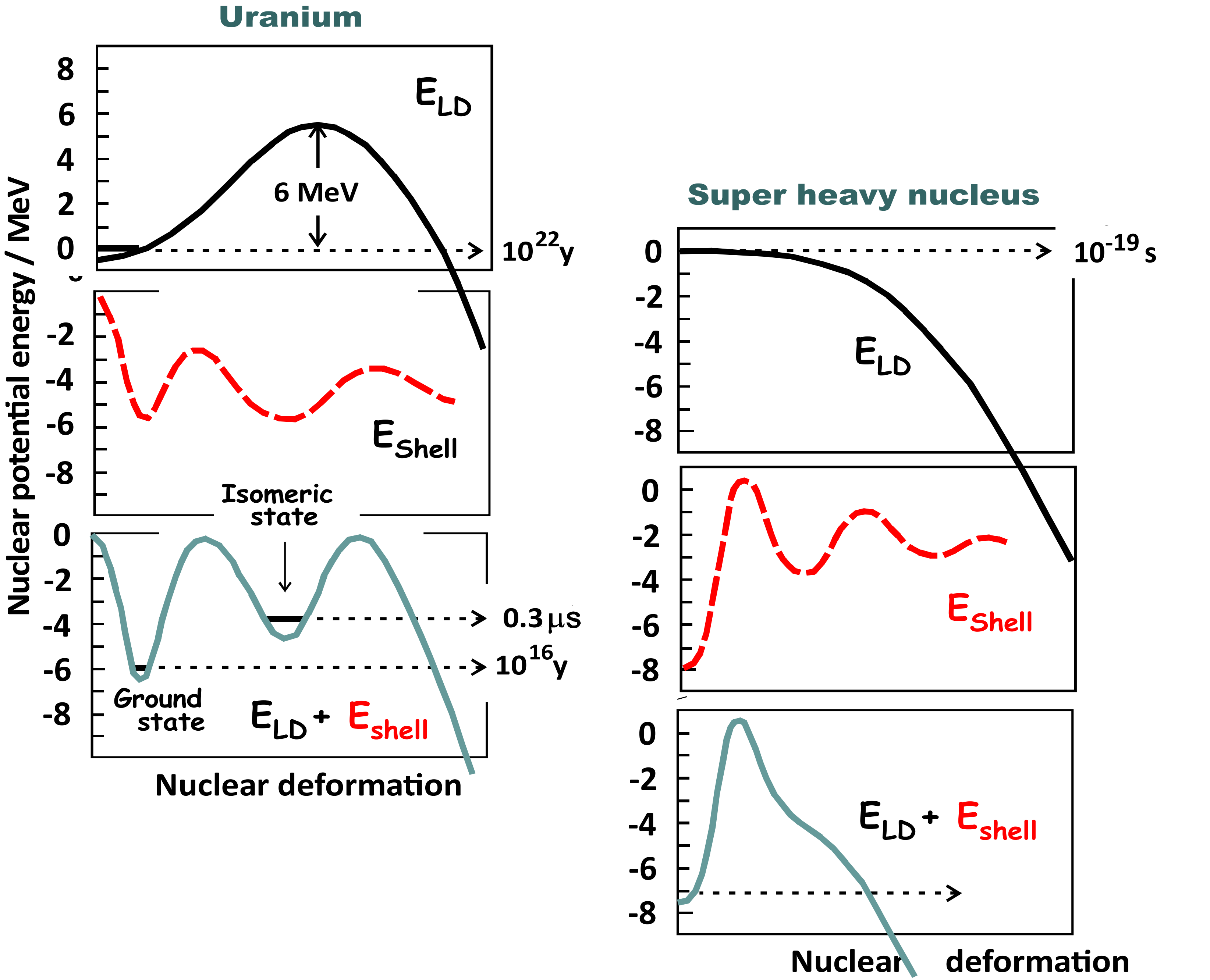
Among them
9 nuclei are doubly magic



Map of the shell corrections (in MeV)
to the liquid drop potential energy



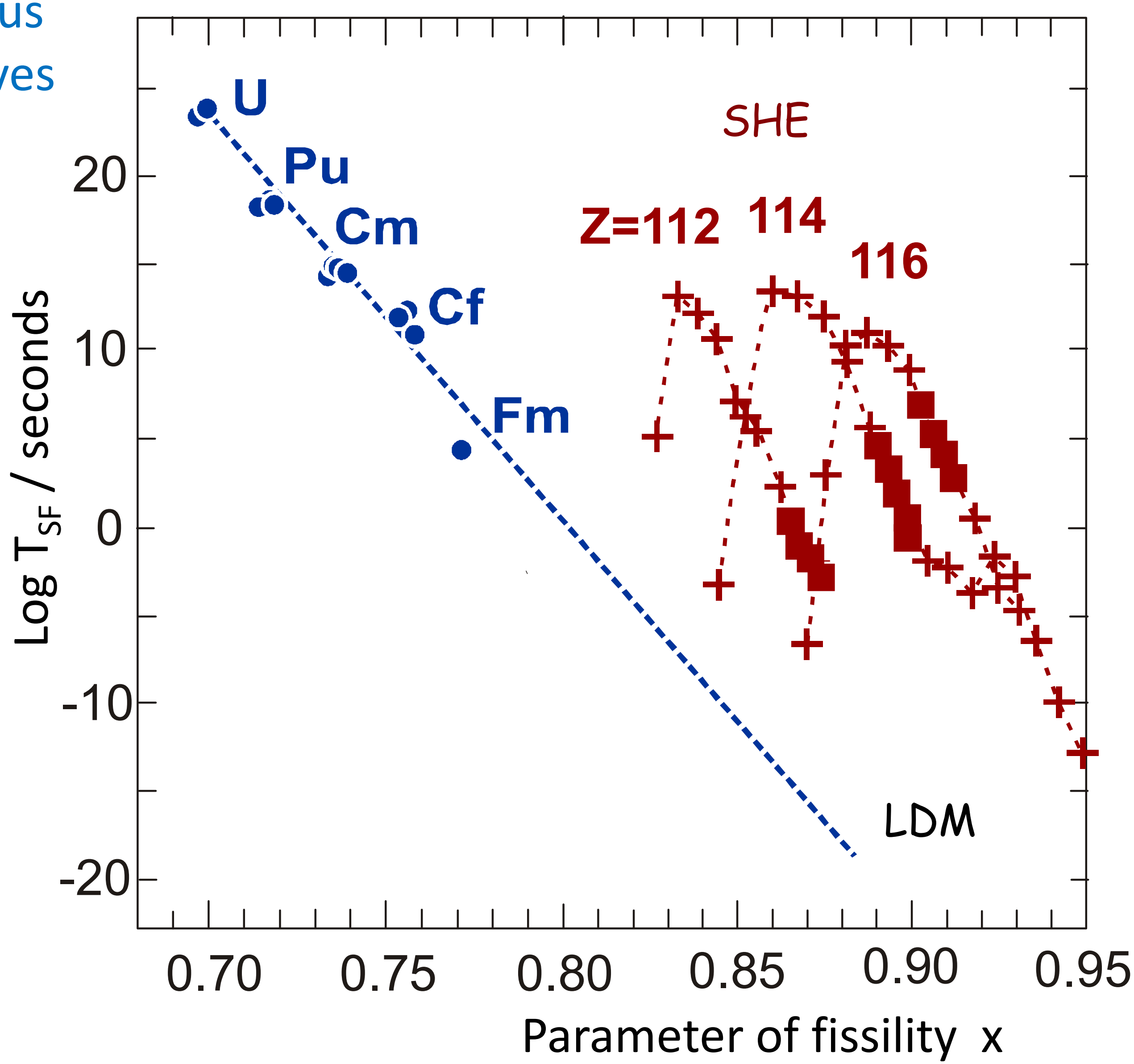
Yuri Oganessian. Discovery of the Island of Stability for SHE. May 19, 2017, Copenhagen, Denmark

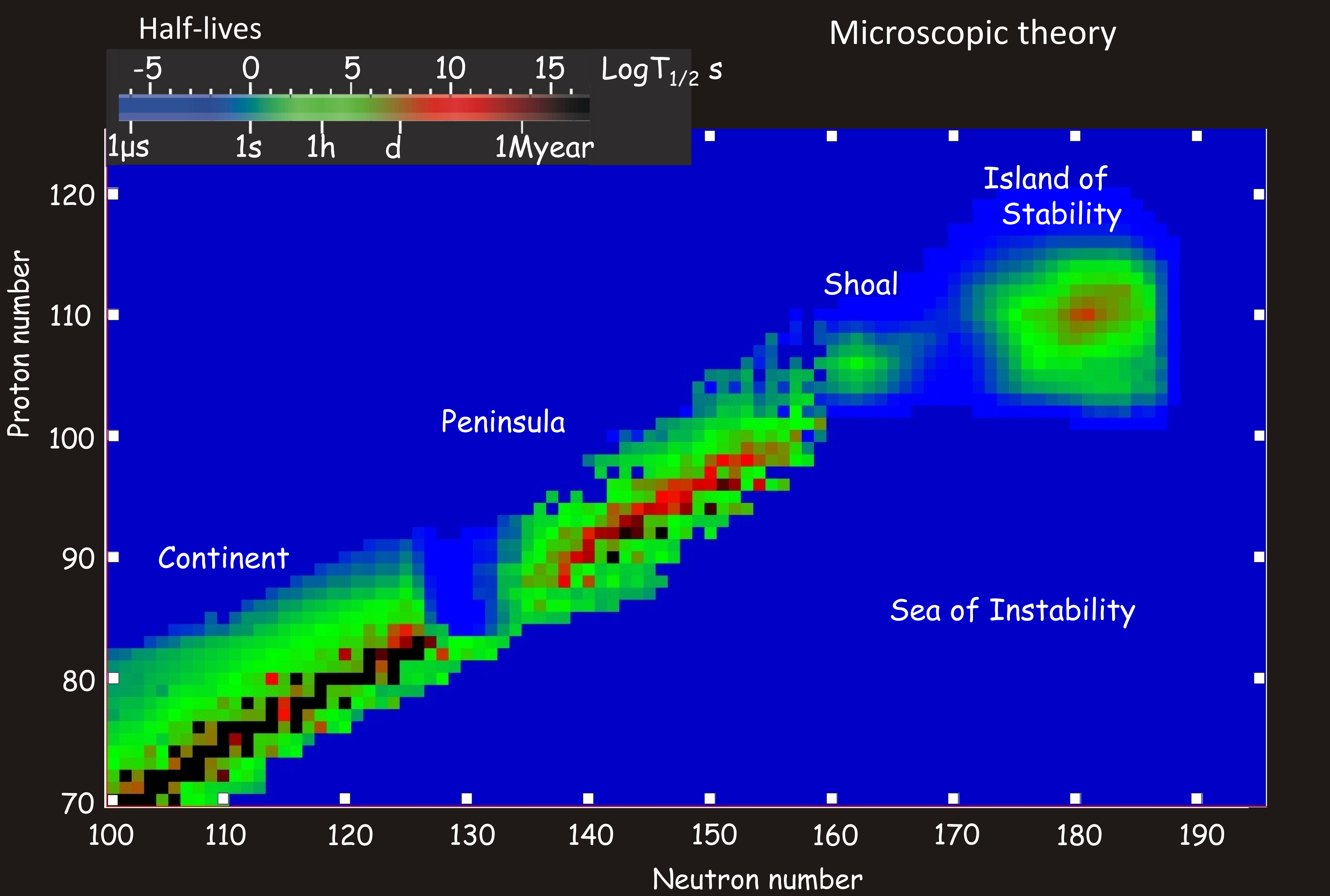


Uranium
Nuclear potential energy / MeV
8
6
4
2
0
E_LD
6 MeV
10^22 y
-2
-4
-6
-8
E_Shell
Isomeric state
0
-2
-4
-6
-8
0.3 µs
10^16 y
Ground state
E_LD + E_shell
Nuclear deformation
Super heavy nucleus
0
-2
-4
-6
-8
10^-19 s
E_LD
0
-2
-4
-6
-8
E_Shell
0
-2
-4
-6
-8
E_LD + E_shell
Nuclear deformation

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

Partial Spontaneous Fission Half-Lives





Microscopic theory
Half-lives
-5
0
5
10
15
$\mathrm{LogT}_{1/2}$ s
1μs
1s
1h
d
1Myear
Island of
Stability
Shoal
Peninsula
Continent
Sea of Instability
Proton number
120
110
100
90
80
70
100
110
120
130
140
150
160
170
180
190
Neutron number

Experimenters rushed to find this island

15-year long assault on the "Islands of Stability"

1970-1985

Los Alamos (USA)

Berkeley (USA)

Dubna (JINR)

Oak Ridge (USA)

Mainz (Germany)

Darmstadt (Germany)

Orsay (France)

Würenlingen (Switzerland)

Tokyo (Japan) some later

The task was:

To find the method of producing/detecting of superheavy elements

Search in nature: earth/lunar objects, cosmic rays,
artificial synthesis of superheavy elements

Use and develop a setup for synthesizing SHE

High-flux reactor, even nuclear explosion, powerful accelerator of heavy ions,

To develop setups and detectors for separating and registering the rarest events of formation and decay of superheavy nuclei

separator/detector, spectrometer, chemical methods, etc.

To have much patience

To work for many years, being ready to rearrange on the way and improve the experimental technique

The task was:

To find the method of producing/detecting of … elements

Search in nature: earth/lunar objects, …

artificial synthesis … nts

Use and develop a setup for sy…

Hig… nuclear explosion, powerful accelerator of heavy ions,

SHE were not found

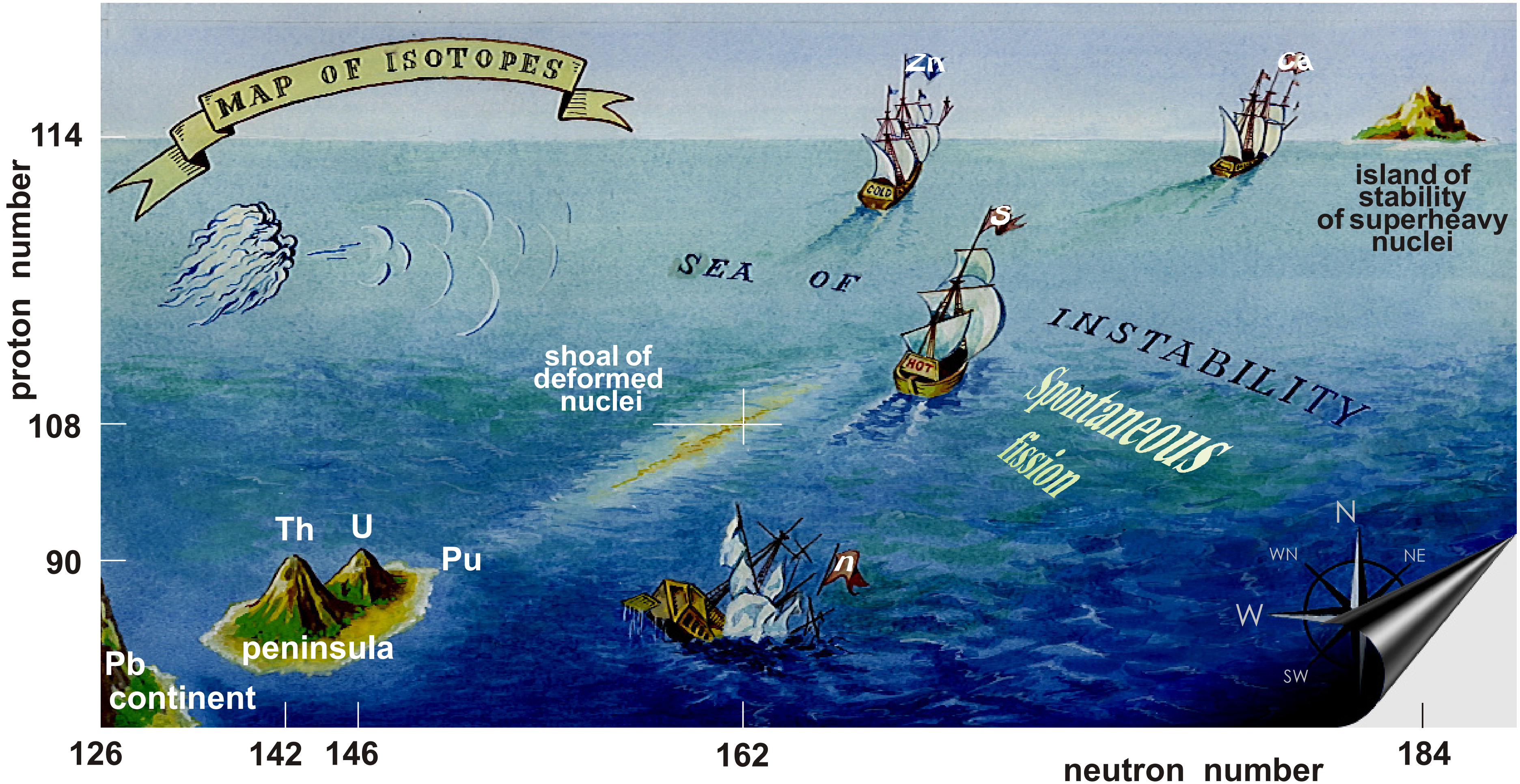
To develop setu… separating and registering the rarest events … decay of superheavy nuclei

… detector, spectrometer, chemical methods, etc.

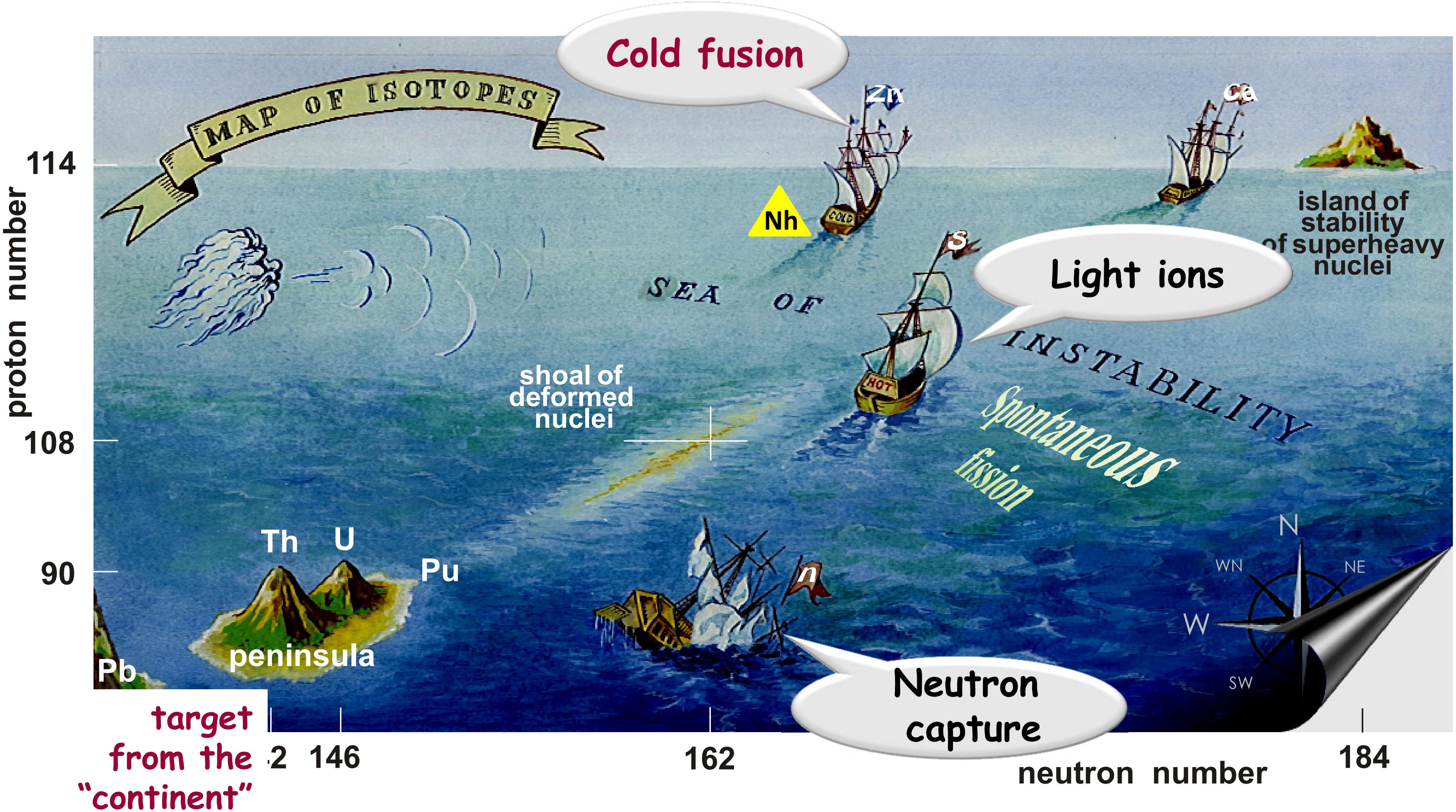
To have much p… nce

To work for many years, being ready to rearrange on the way and improve the experimental technique

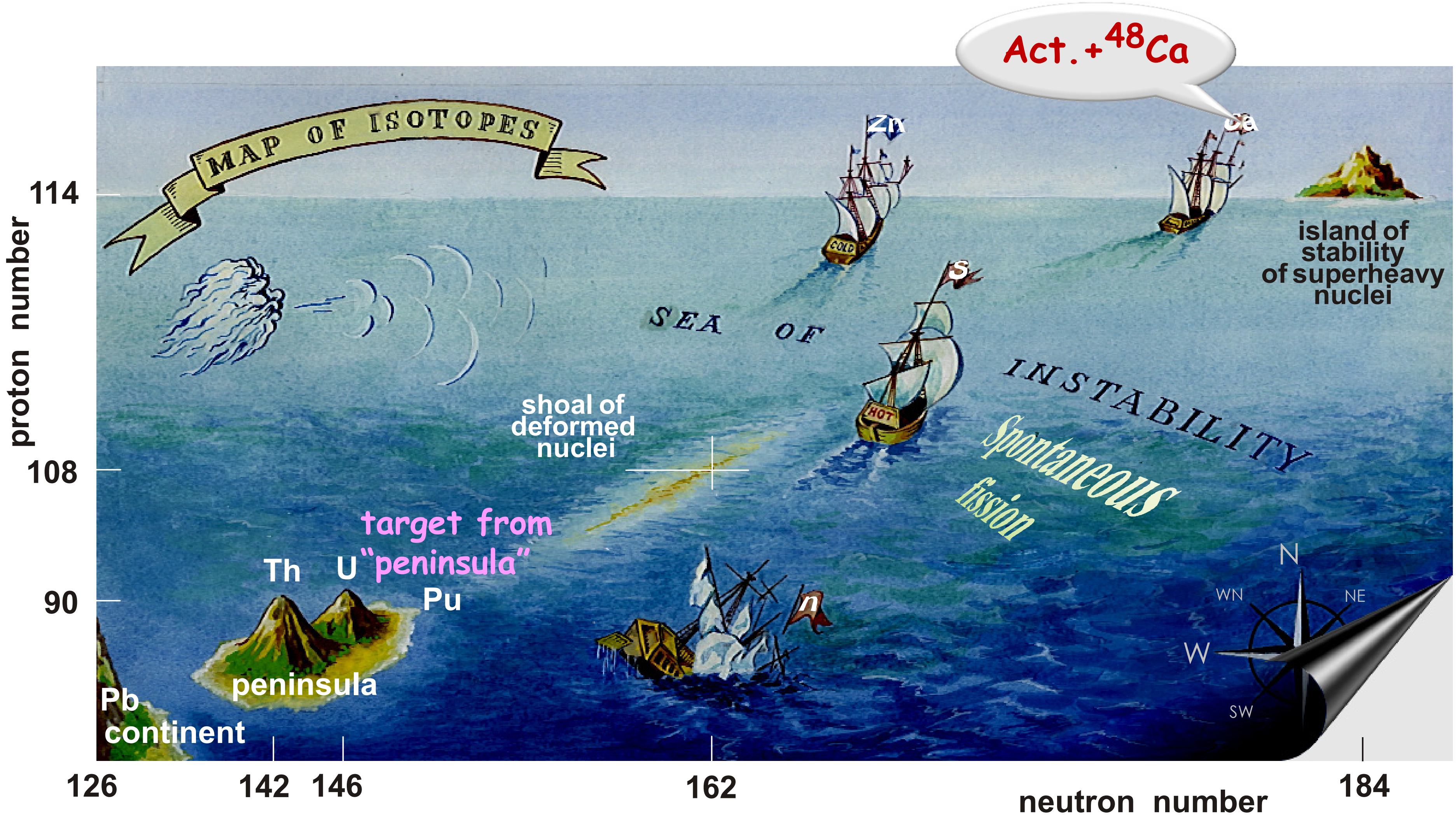
Reactions of synthesis



Reactions of synthesis



Our new approach greatly complicates the experiment



artificial element from
flux nuclear reactor

target

from
accelerator

to separator

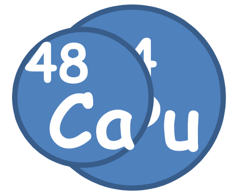
projectiles

rare and very
expensive isotope of Ca

artificial element from
flux nuclear reactor

target

from
accelerator



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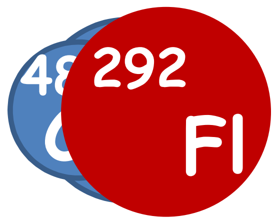

to separator

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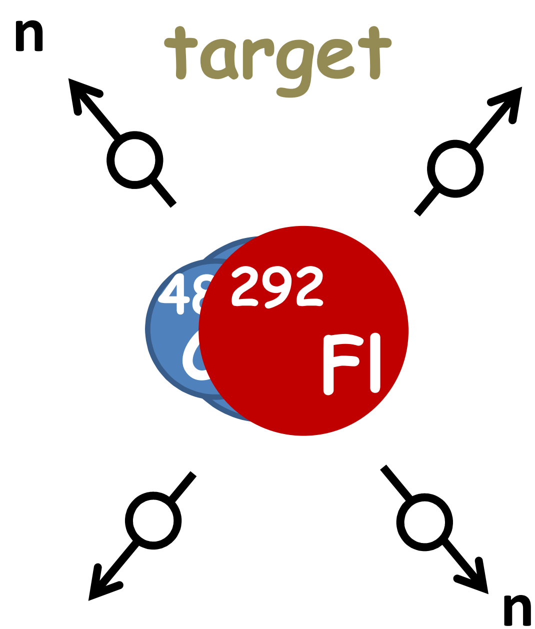


from
accelerator

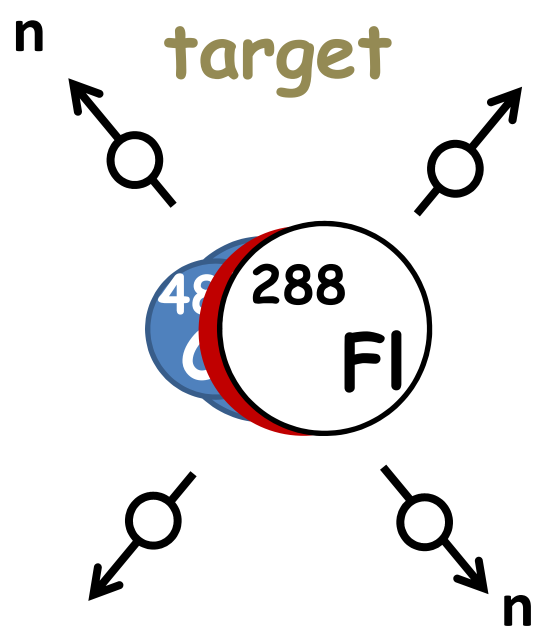
to separator

projectiles

rare and very
expensive isotope of Ca

artificial element from
flux nuclear reactor

target



from
accelerator

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rare and very
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artificial element from
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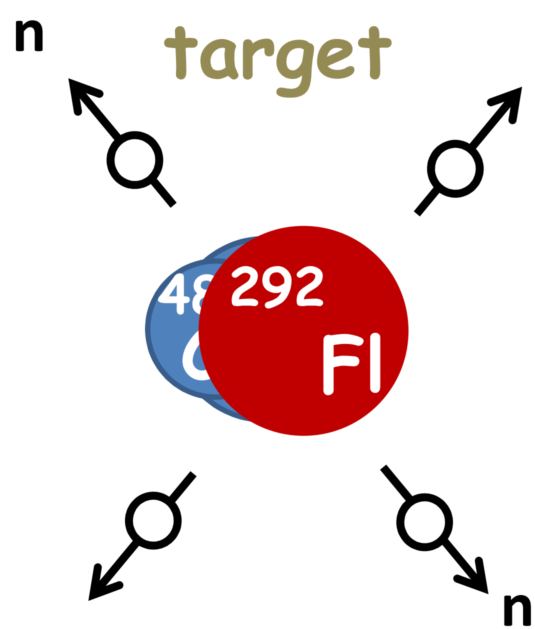
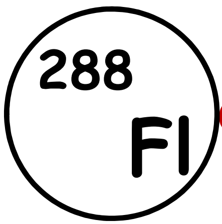
target





eparator

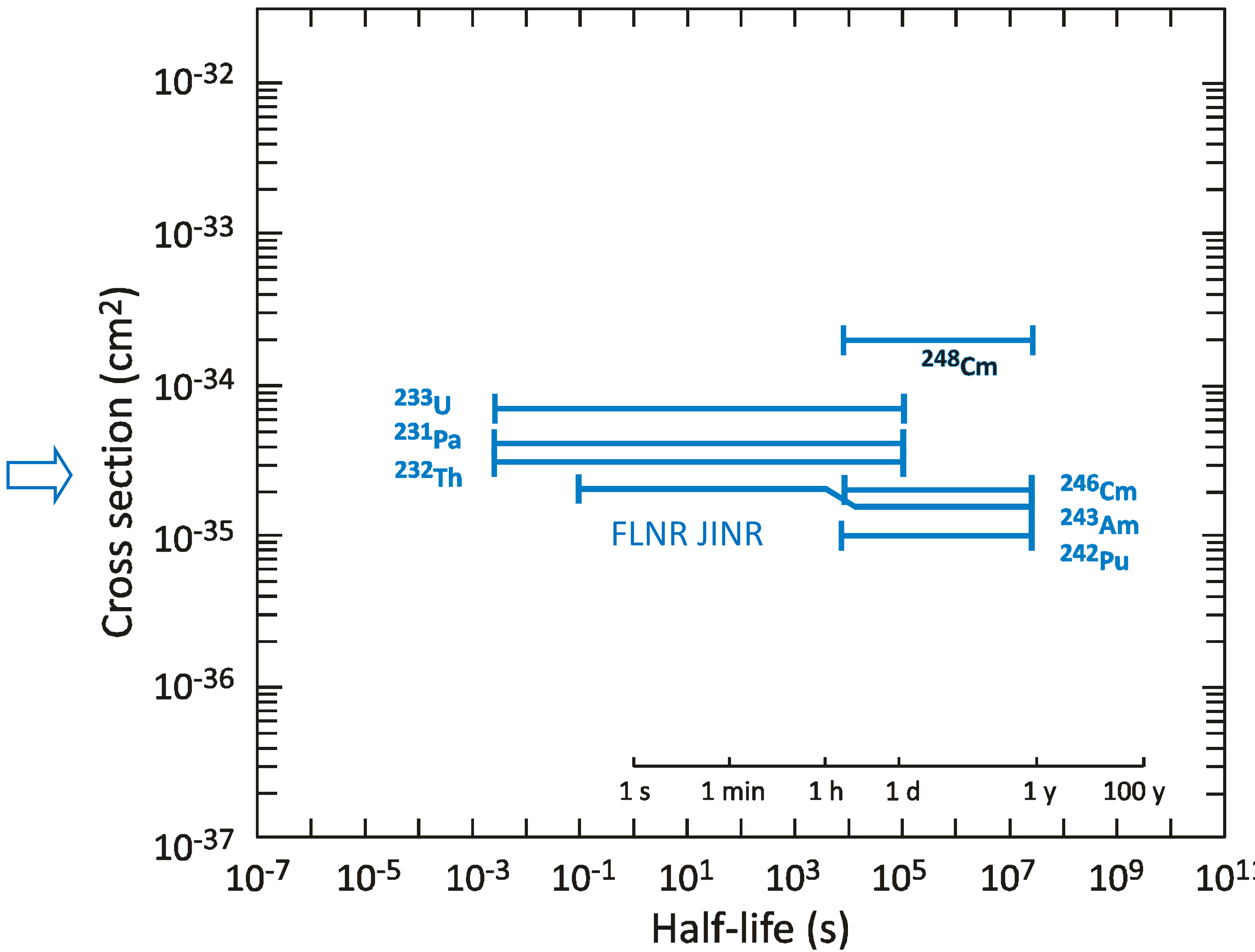
from
accelerator

projectiles

rare and very
expensive isotope of Ca

Experiments on the synthesis of SHE with ^{48}Ca-beam at FLNR (JINR)

1977- 1979

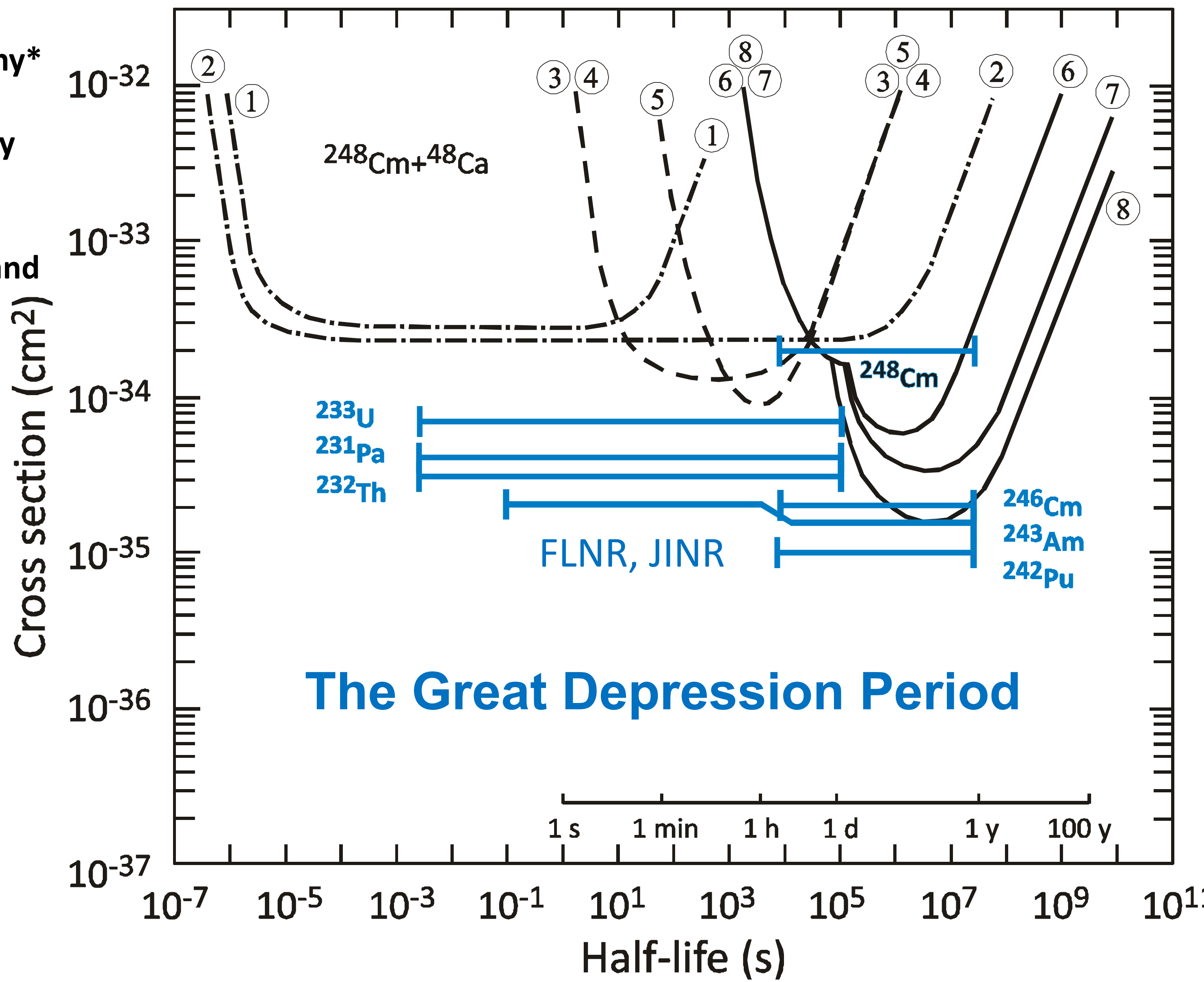


Experiments on the synthesis of Z=116 nuclei in the reaction $^{248}Cm+^{48}Ca$

GSI, Darmstadt, Germany*
LBL, UC Berkeley, CA
Univ. of Mainz, Germany
LANL, Los Alamos, NM
EIR, Würenlingen, Switzerland

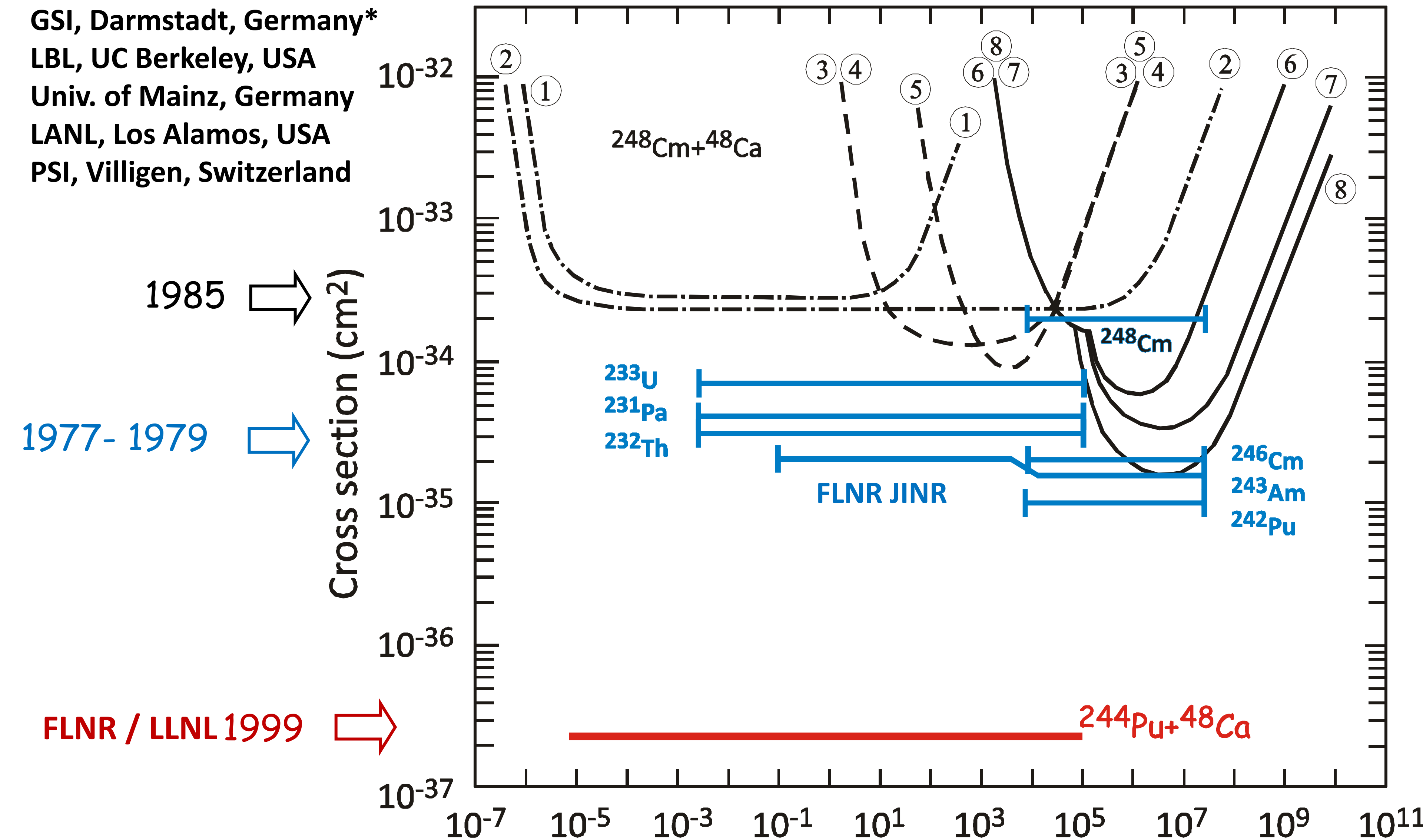
1985

1977- 1979



Experiments on the synthesis of SHE in ^{48}Ca induced reaction

GSI, Darmstadt, Germany*
LBL, UC Berkeley, USA
Univ. of Mainz, Germany
LANL, Los Alamos, USA
PSI, Villigen, Switzerland



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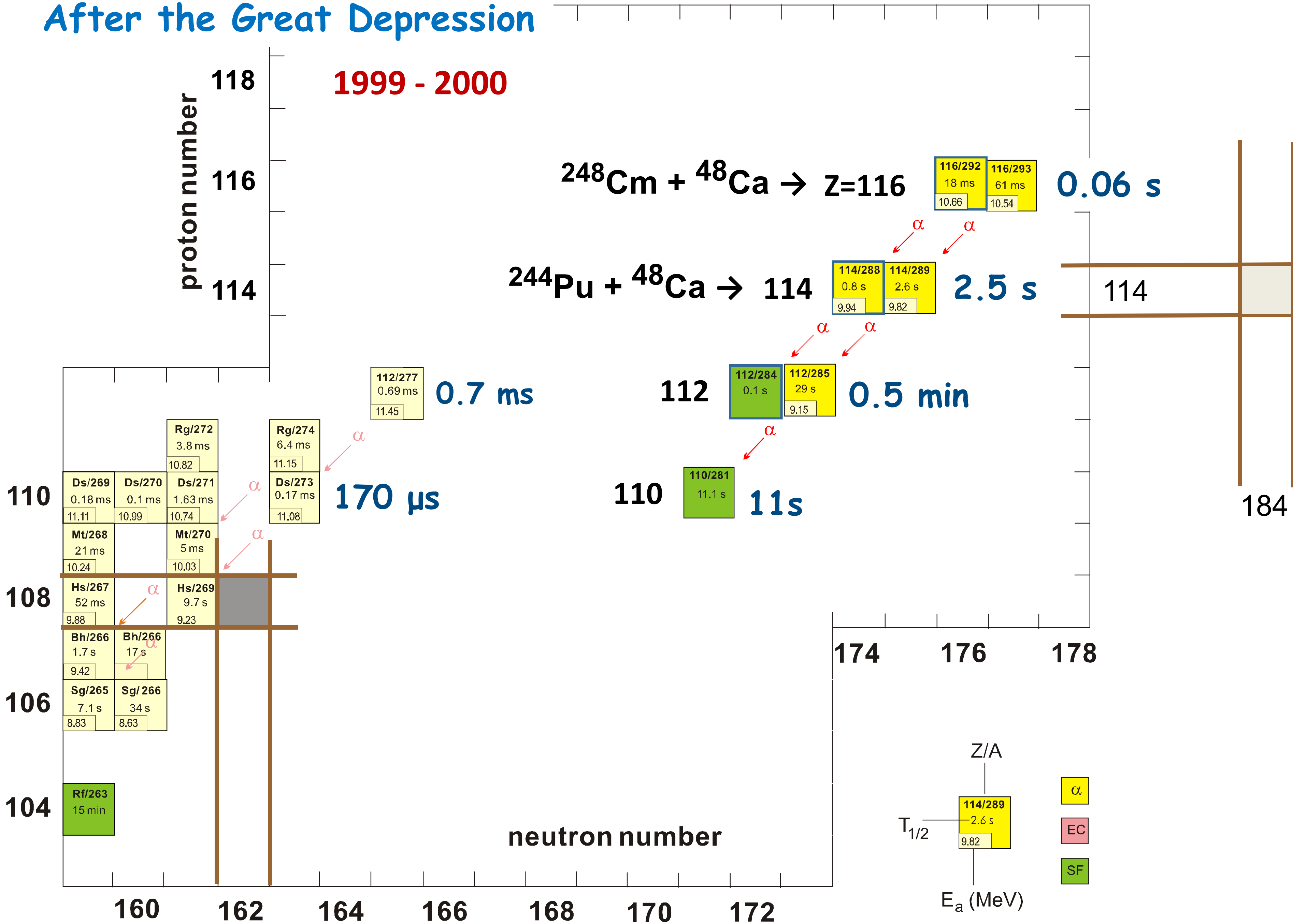
After the Great Depression



an Article from SCIENTIFIC AMERICAN

JANUARY 2000 VOL. 282 NO. 1

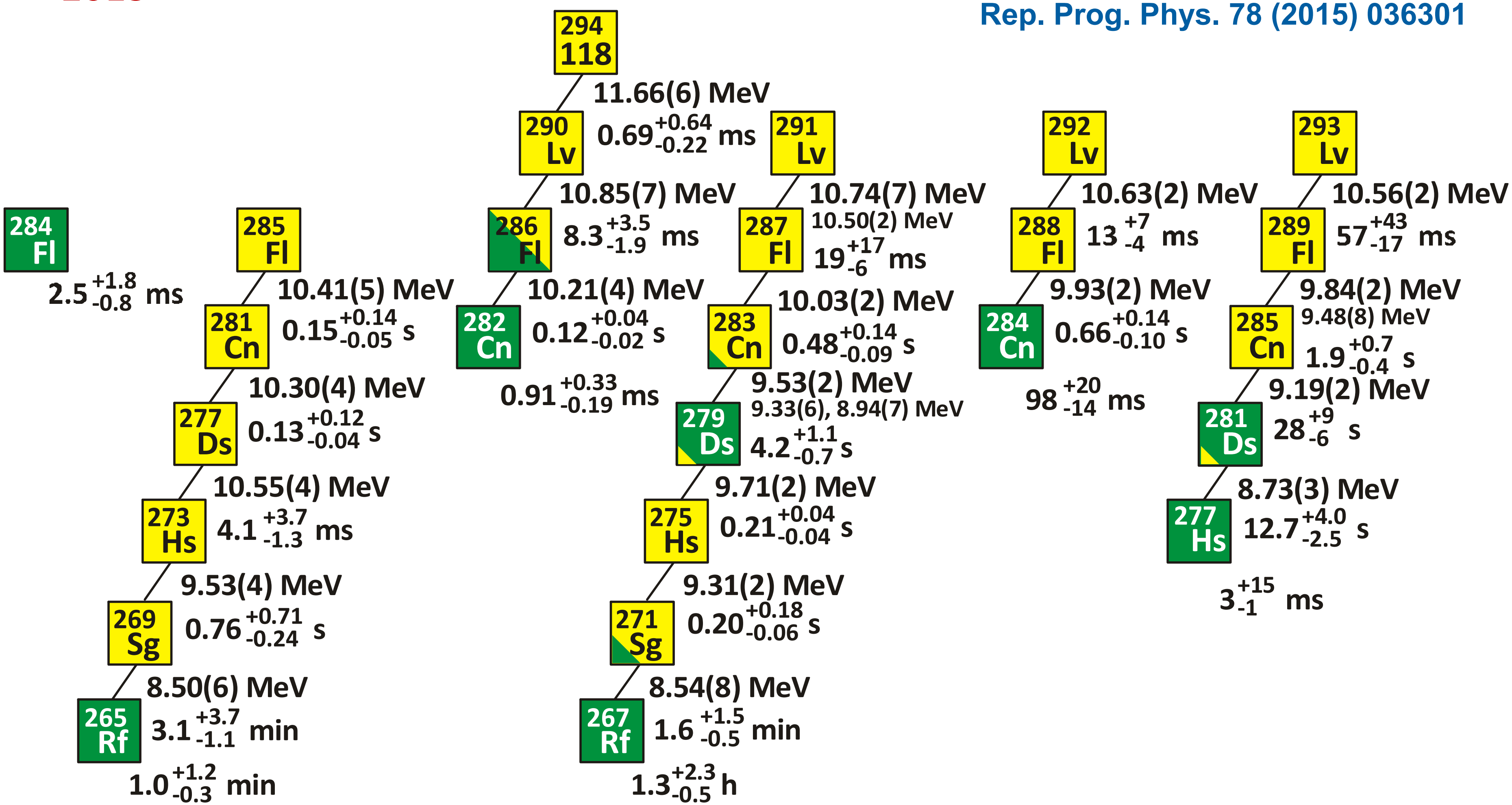
Voyage to SUPERHEAVY Island

The synthesis of element 114 confirmed decades-old theoretical predictions of a little patch of nuclear stability in a sea of short-lived superheavy nuclei

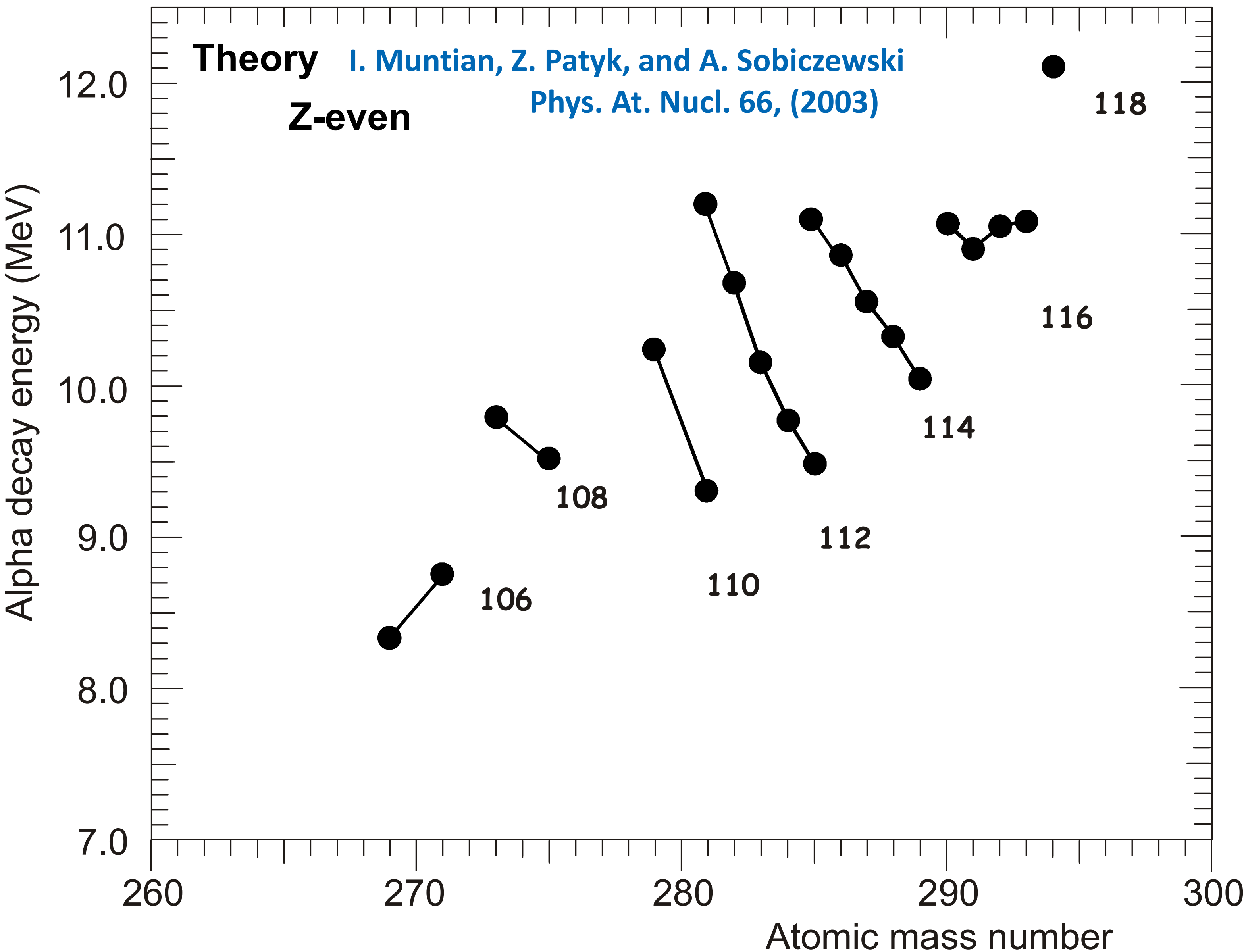
Summary decay properties of the isotopes of elements 112, 114, 116 and 118 observed in ^{238}U, ^{240,242,244}Pu, ^{245,248}Cm and ^{249}Cf + ^{48}Ca reactions

2015

Yu Ts Oganessian and V K Utyonkov,
Rep. Prog. Phys. 78 (2015) 036301

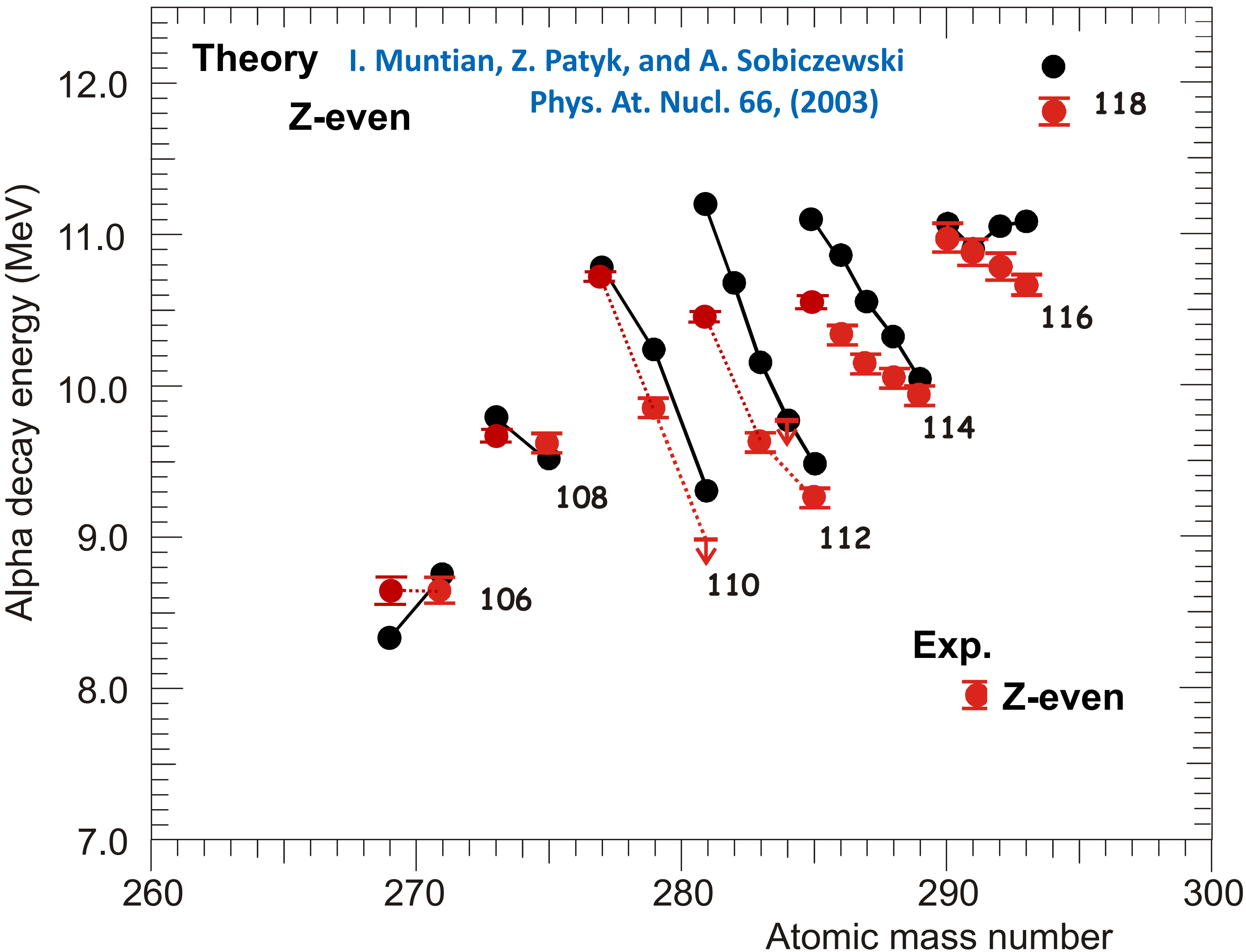


Alpha - decay



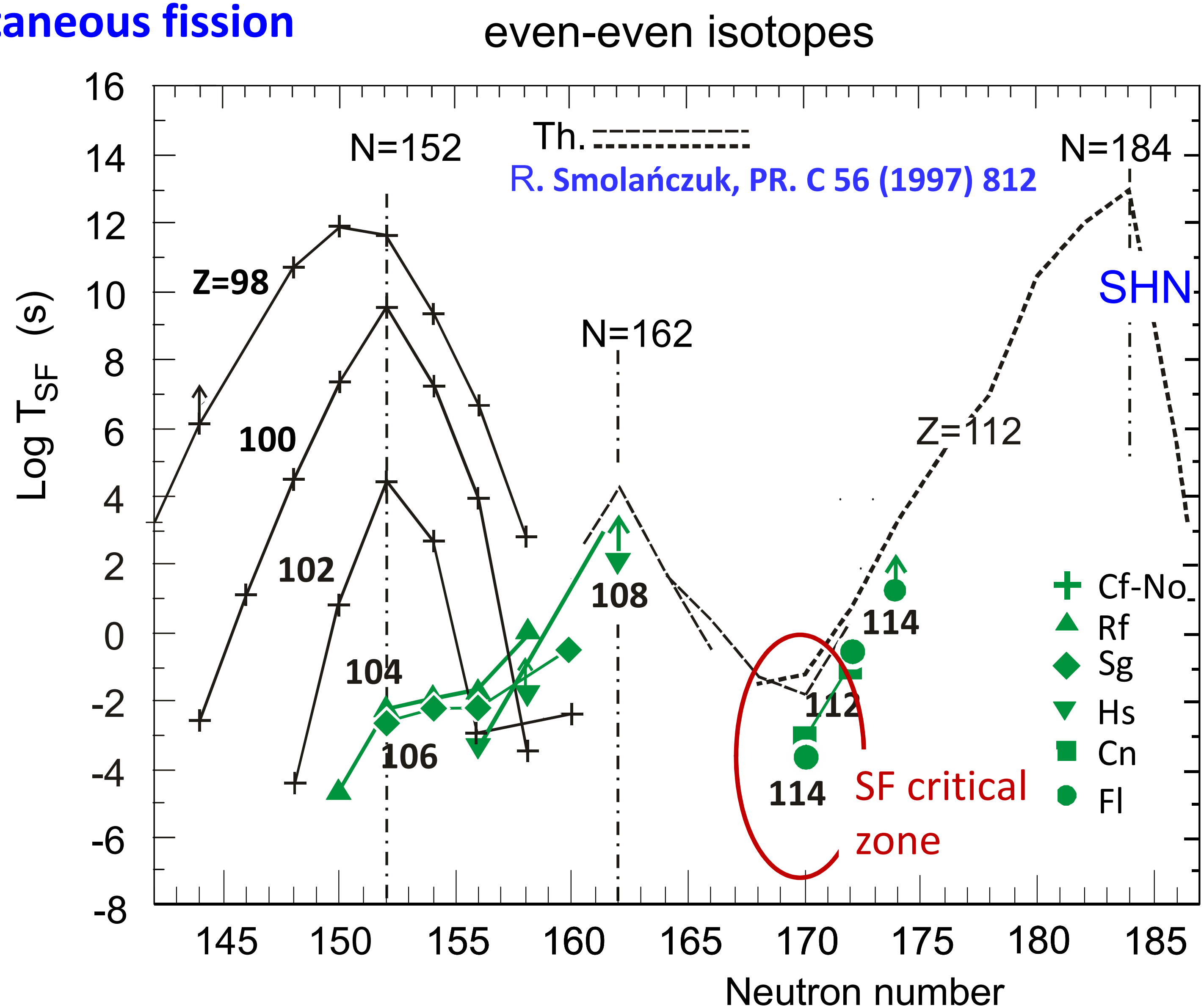
Theory
Z-even
I. Muntian, Z. Patyk, and A. Sobiczewski
Phys. At. Nucl. 66, (2003)
Alpha decay energy (MeV)
Atomic mass number
7.0
8.0
9.0
10.0
11.0
12.0
260
270
280
290
300
106
108
110
112
114
116
118

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



Cross sections

hot fusion

$^{48}Ca + ^{238}U, \ldots\ldots ^{249}Cf$

E_x = 40 - 45 MeV

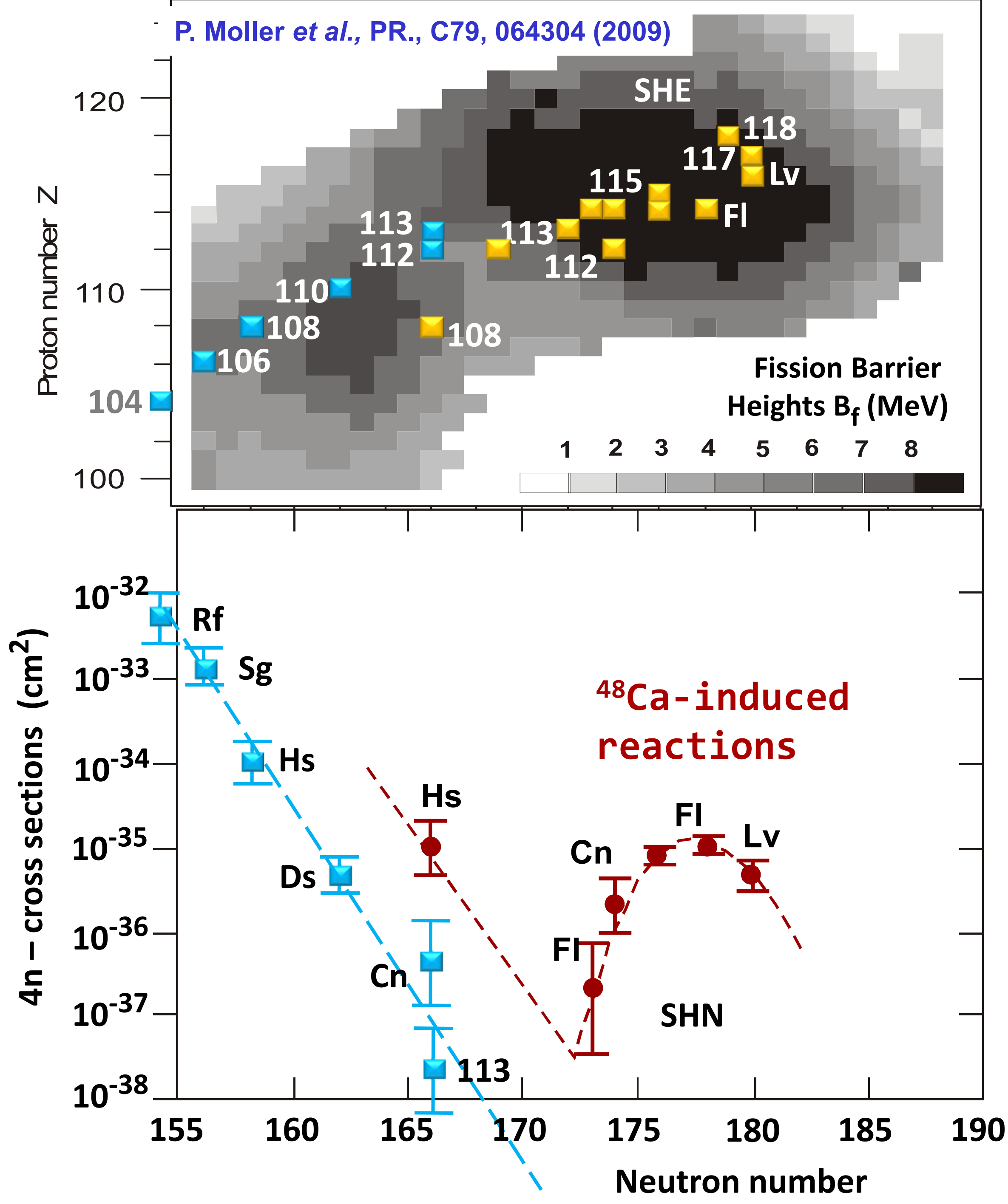
$x = 4 - 5$

cold fusion

^{208}Pb, $^{209}Bi + ^{50}Ti, \ldots\ldots ^{70}Zn$

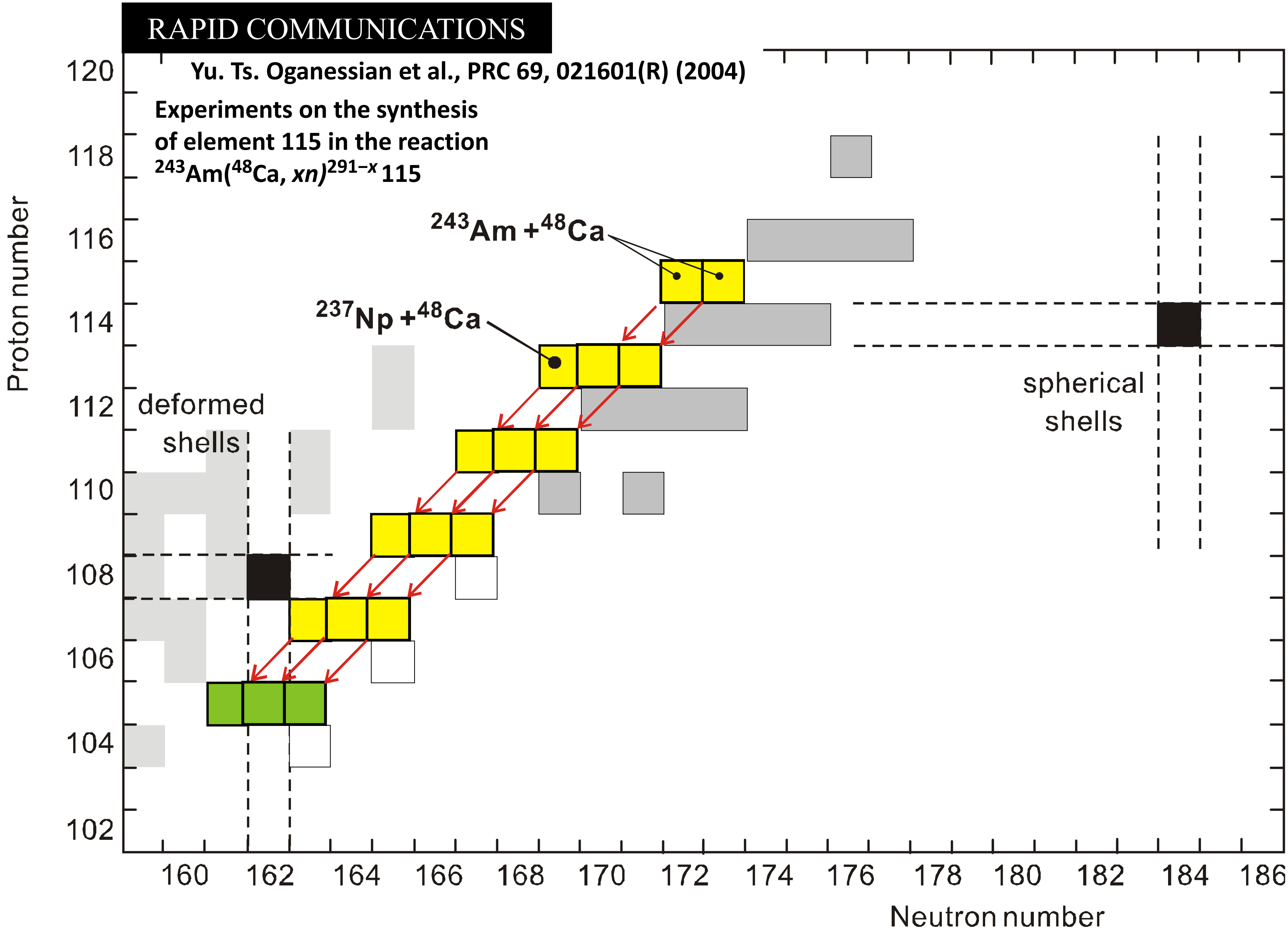
E_x = 12 - 15 MeV

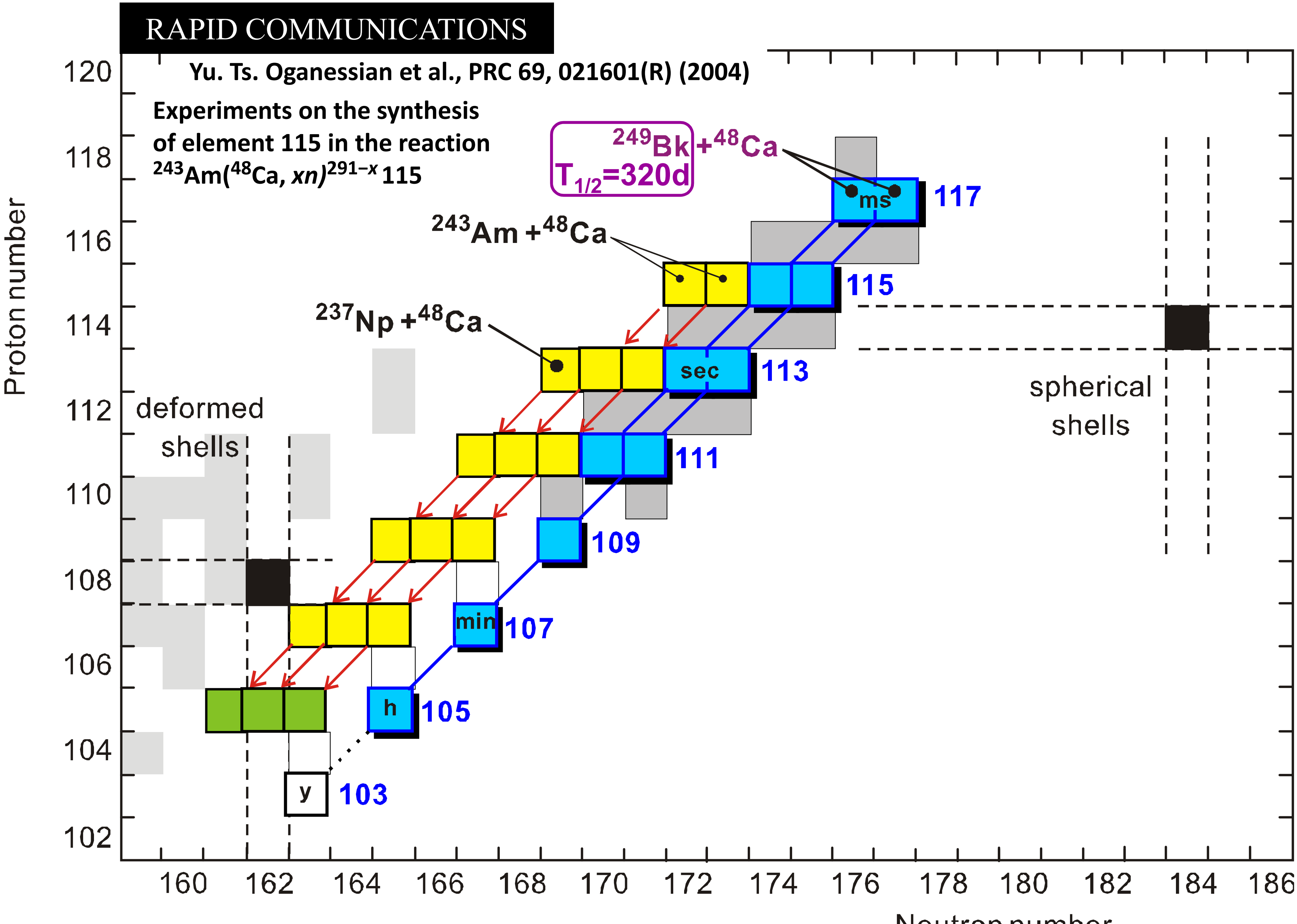
$x = 1$



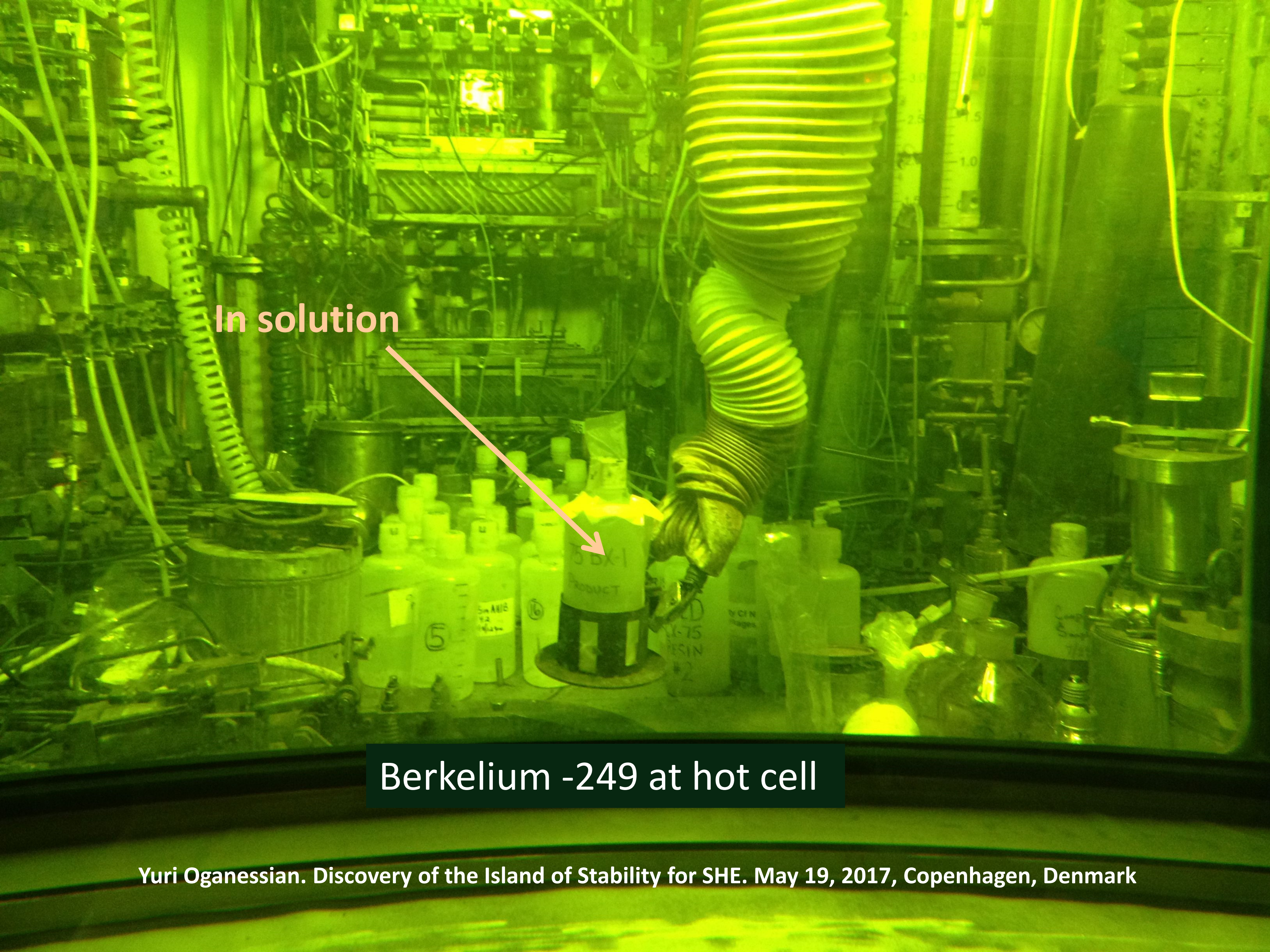
Odd-Z Superheavy Nuclei

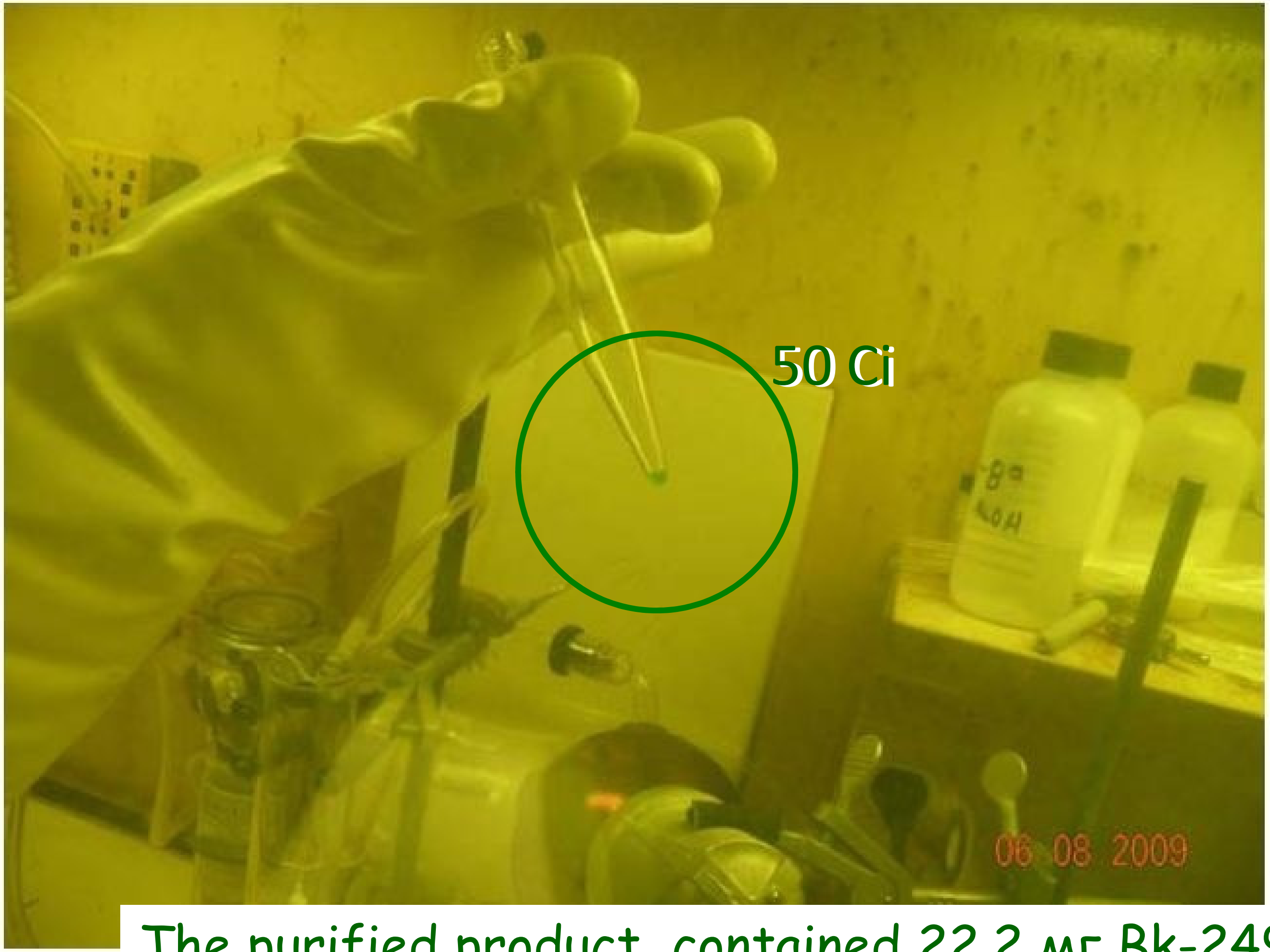
Synthesis of the Isotopes with Z =113, 115 and 117


RAPID COMMUNICATIONS
Yu. Ts. Oganessian et al., PRC 69, 021601(R) (2004)
Experiments on the synthesis
of element 115 in the reaction
$^{243}Am(^{48}Ca, xn)^{291-x}115$
$^{243}Am + ^{48}Ca$
$^{237}Np + ^{48}Ca$
deformed
shells
spherical
shells
Proton number
Neutron number
120
118
116
114
112
110
108
106
104
102
160
162
164
166
168
170
172
174
176
178
180
182
184
186



Yuri Oganessian. Discovery of the Island of Stability for SHE. May 19, 2017, Copenhagen, Denmark


In solution
Berkelium -249 at hot cell

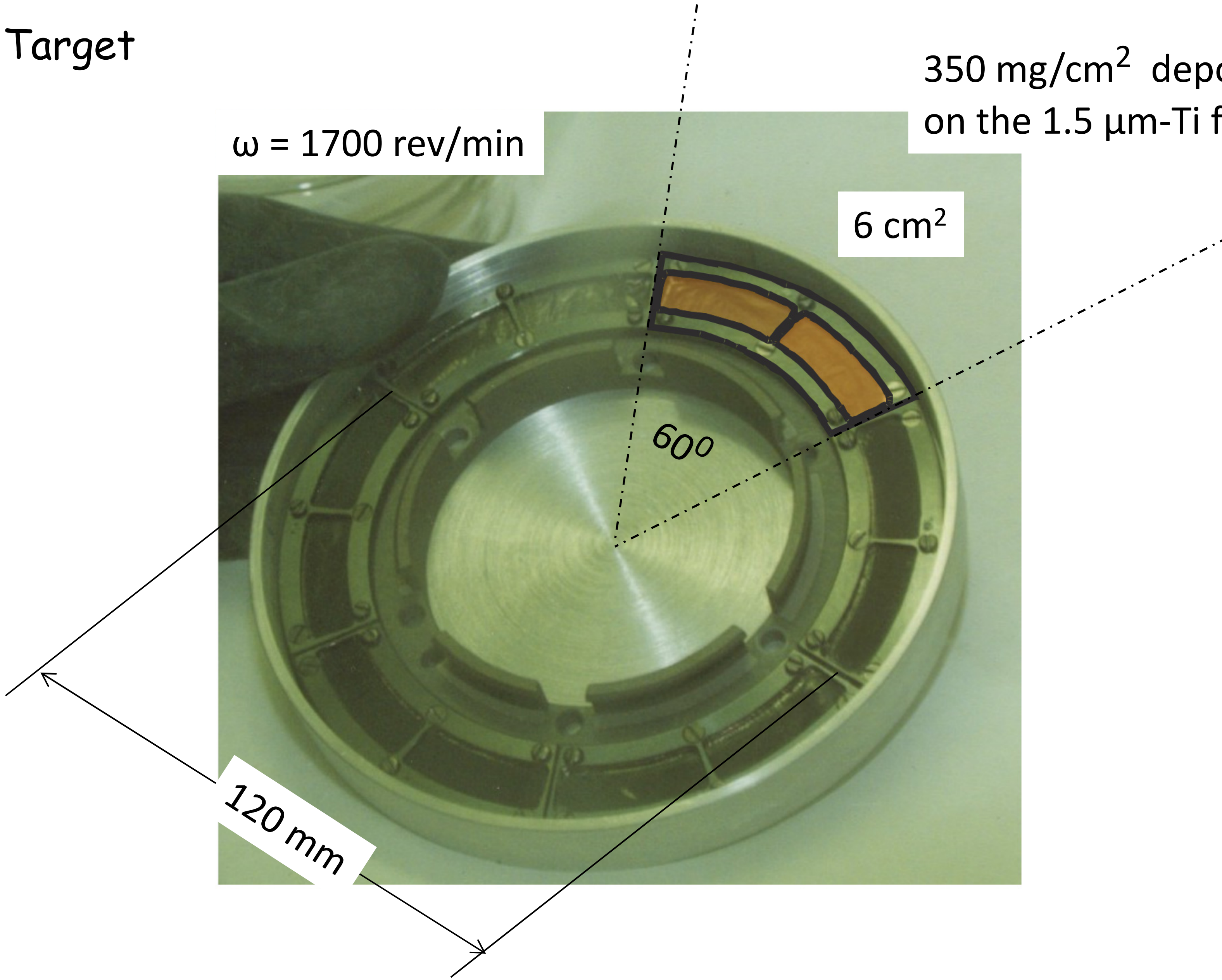


The purified product contained 22.2 мг Bk-249

$Bk(NO_3)_3$Product

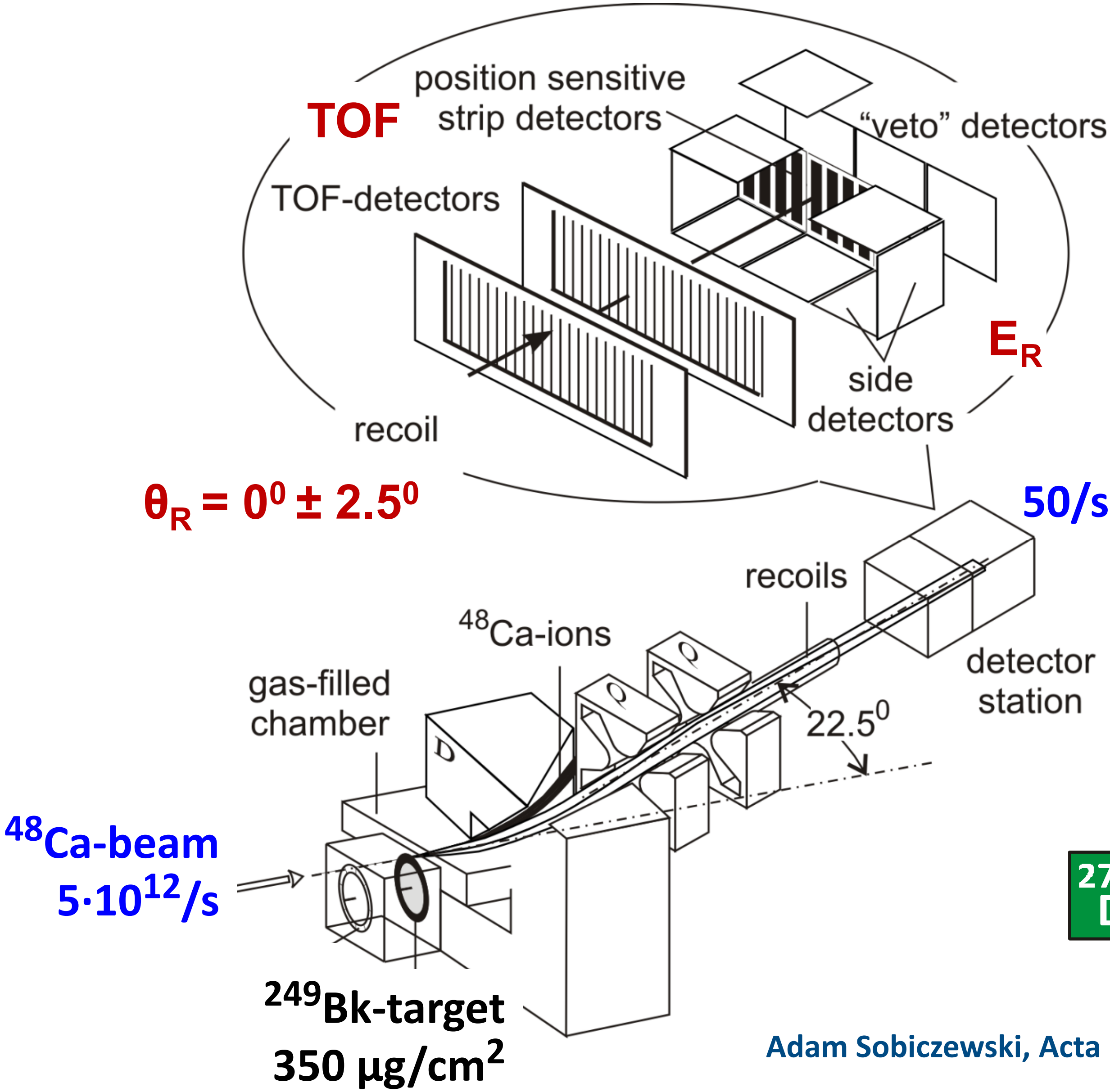
Yu. Oganessian 2010

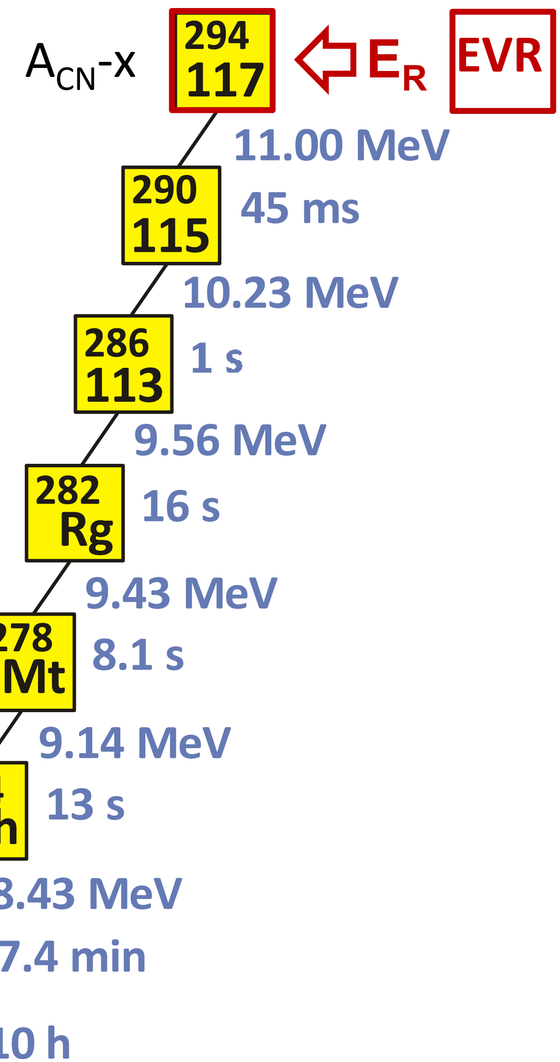
Target



Yu. Oganessian 2010

Dubna Gas-Filled Recoil Separator DGFRS

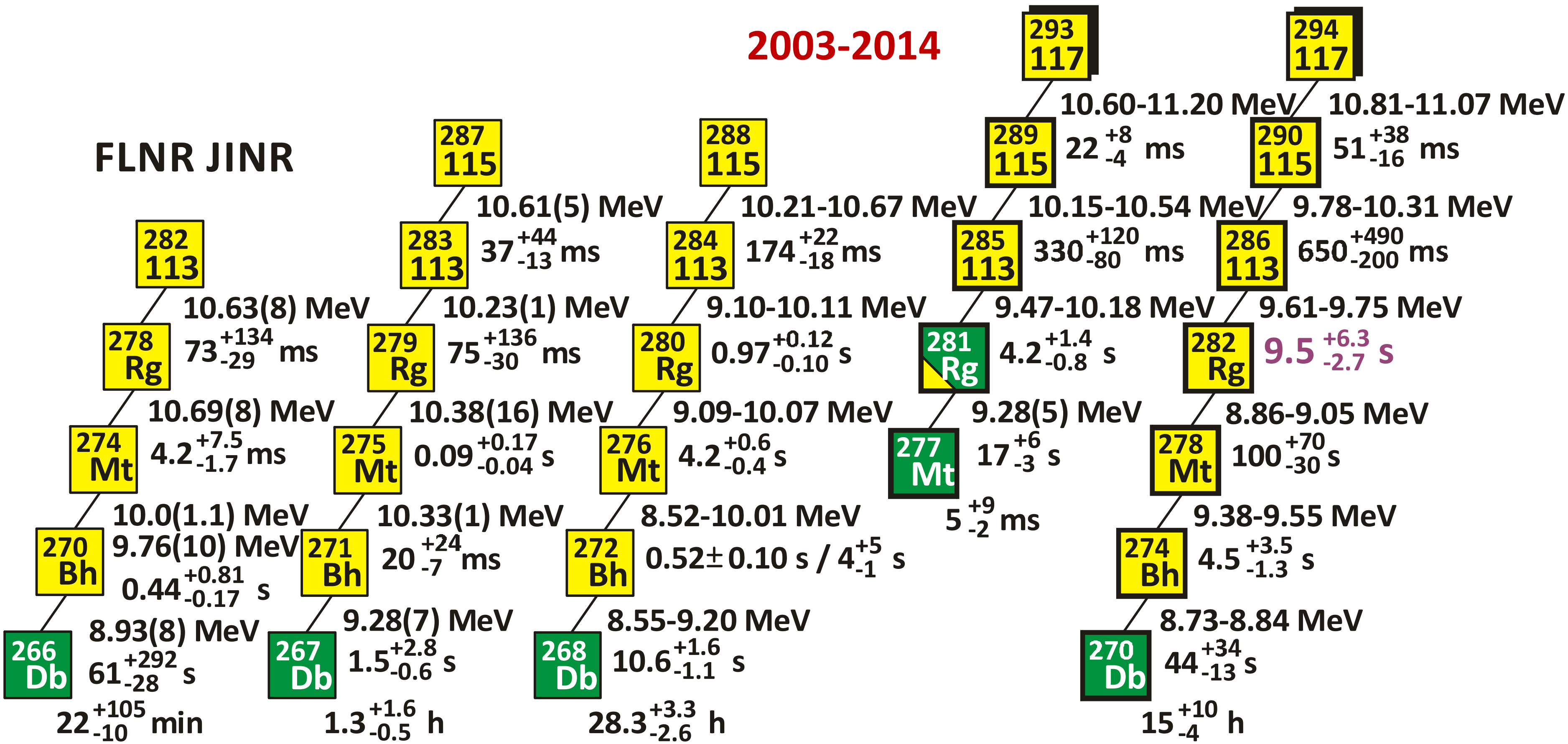




Adam Sobiczewski, Acta Phys. Pol. B 41, 157 (2010).

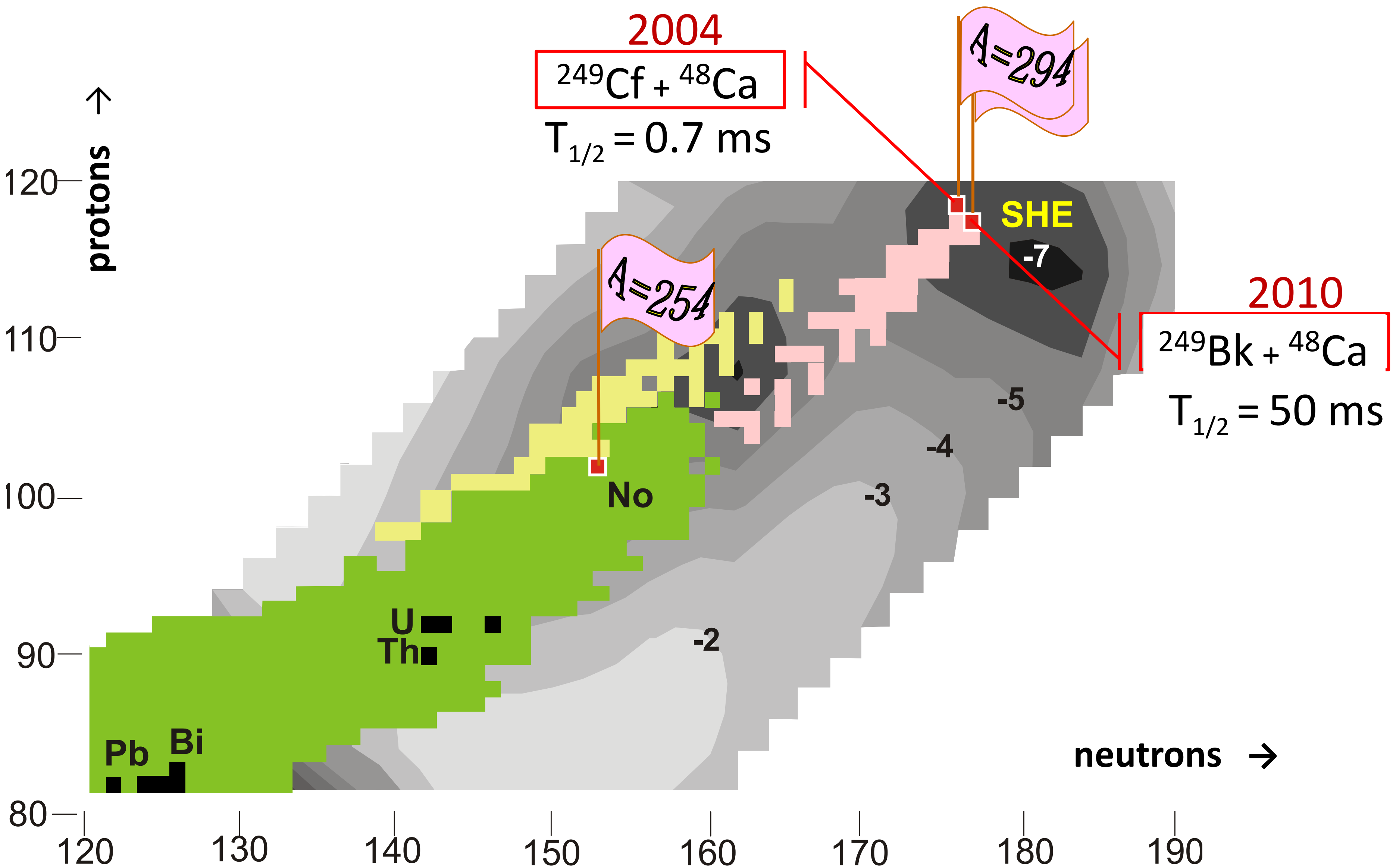

Heavy Ion Accelerator, FLNR

Summary decay properties of the isotopes of elements 113, 115, and 117 observed in ^{237}Np, ^{243}Am and ^{249}Bk + ^{48}Ca reactions



Discovery of the Heaviest Nuclei with Z=112-117 [Confirmations 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)
$^{288,289}114$	TASCA	GSI – Mainz	P.R. Lett. 104, 252701 (2010)
$^{292,293}116$	SHIP	GSI Darmstadt	Eur. Phys. J. A48, 62 (2012)
$^{287,288}115$	TASCA	GSI – Mainz	P.R. Lett. 111, 112502 (2013)
$^{293,294}117$	TASCA	GSI – Mainz	P.R. Lett. 112, 172501 (2014)
$^{292,293}116$	GARIS	RIKEN Tokyo	Accelerator Progress Rep. (2013)



Yuri Oganessian. Discovery of the Island of Stability for SHE. May 19, 2017, Copenhagen, Denmark

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

Although SHN are at the limits of Coulomb stability,

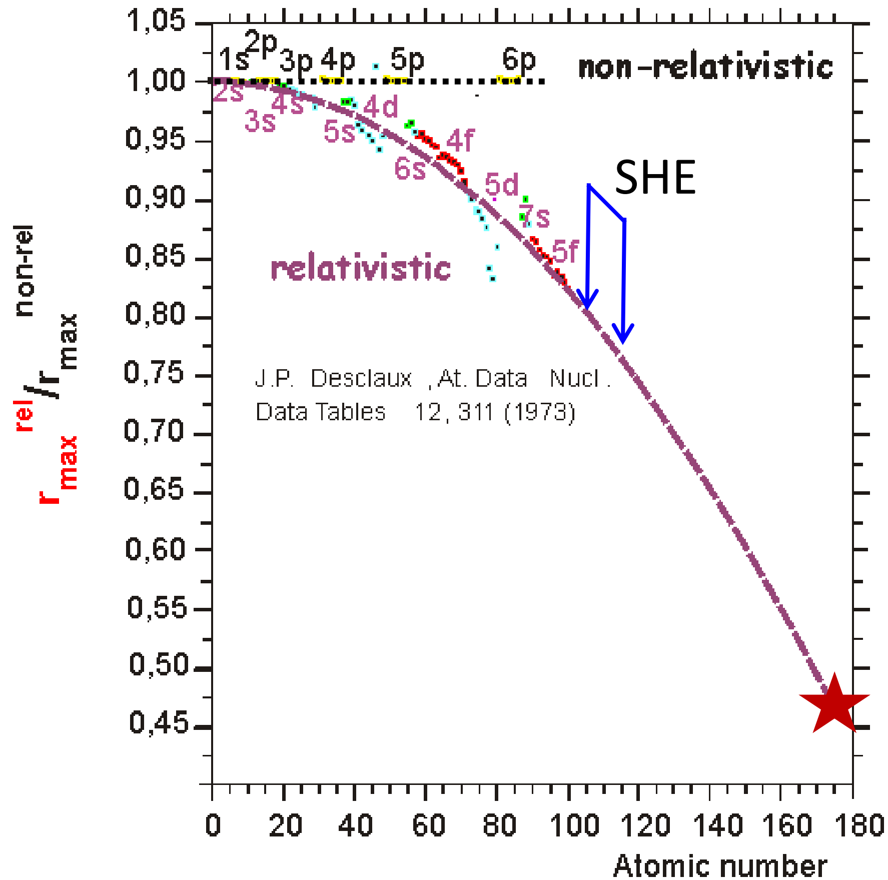
- shell stabilization lowers ground-state energy,
- creates a fission barrier,
- and thereby enables SHN to exist.

.

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

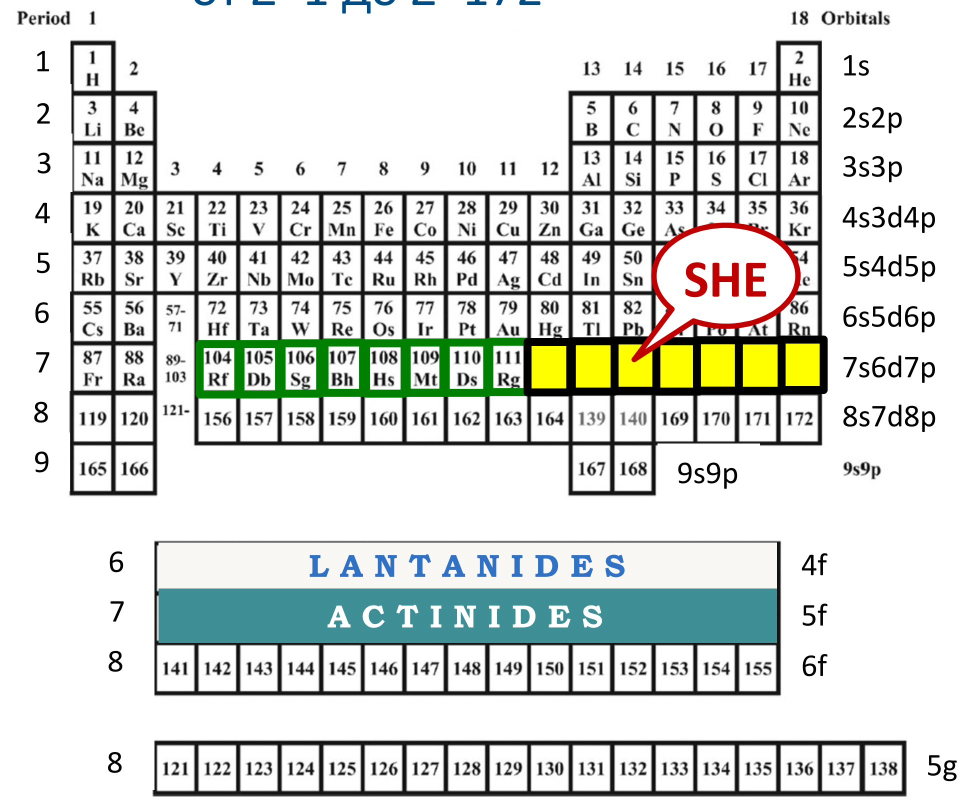
Super Heavy Atoms

Chemistry of the SHE



Relativistic Contraction

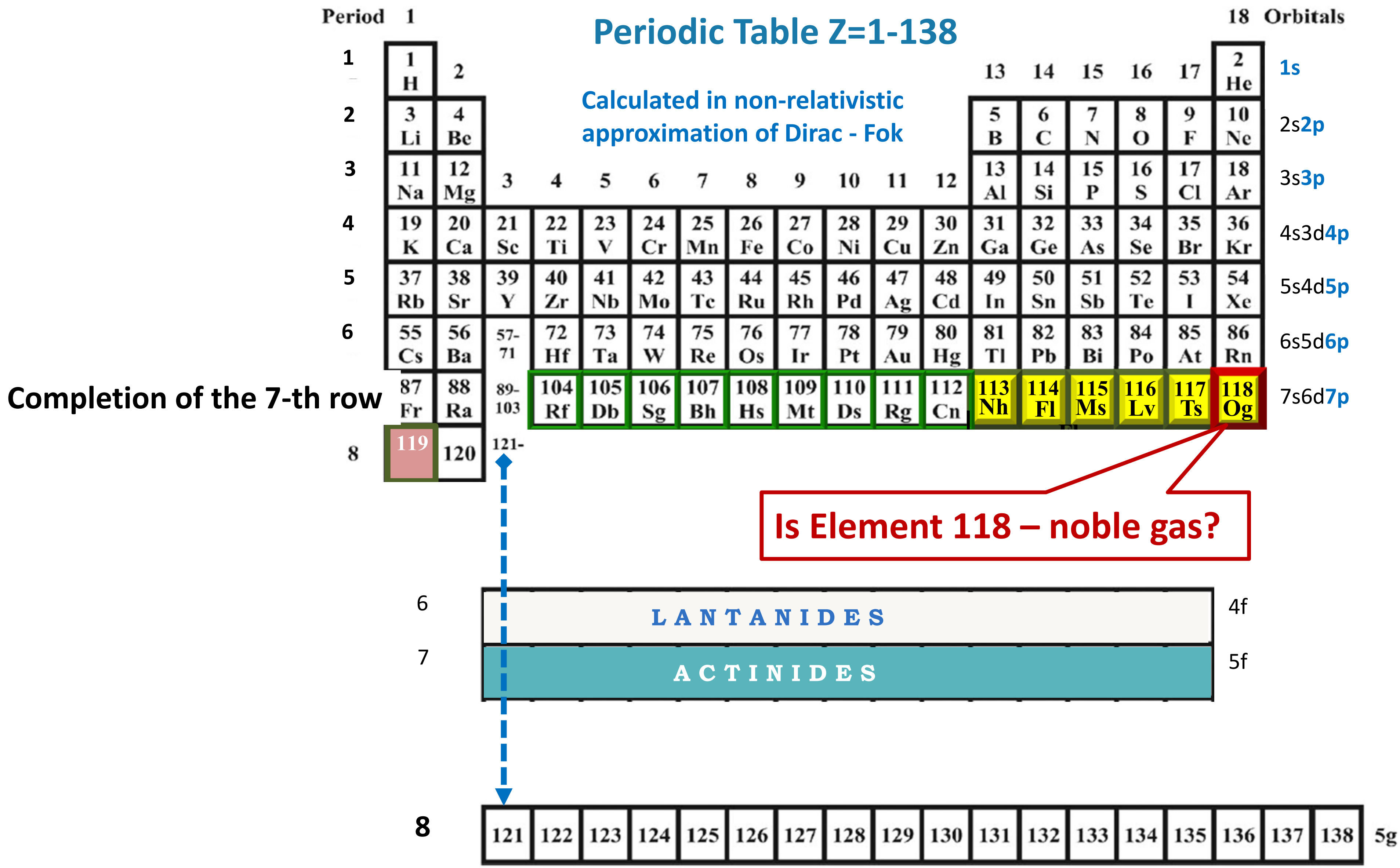
Table of Elements
от Z=1 до Z=172



Calculated by P. Dirac and V. Fock
in non-relativistic approximation

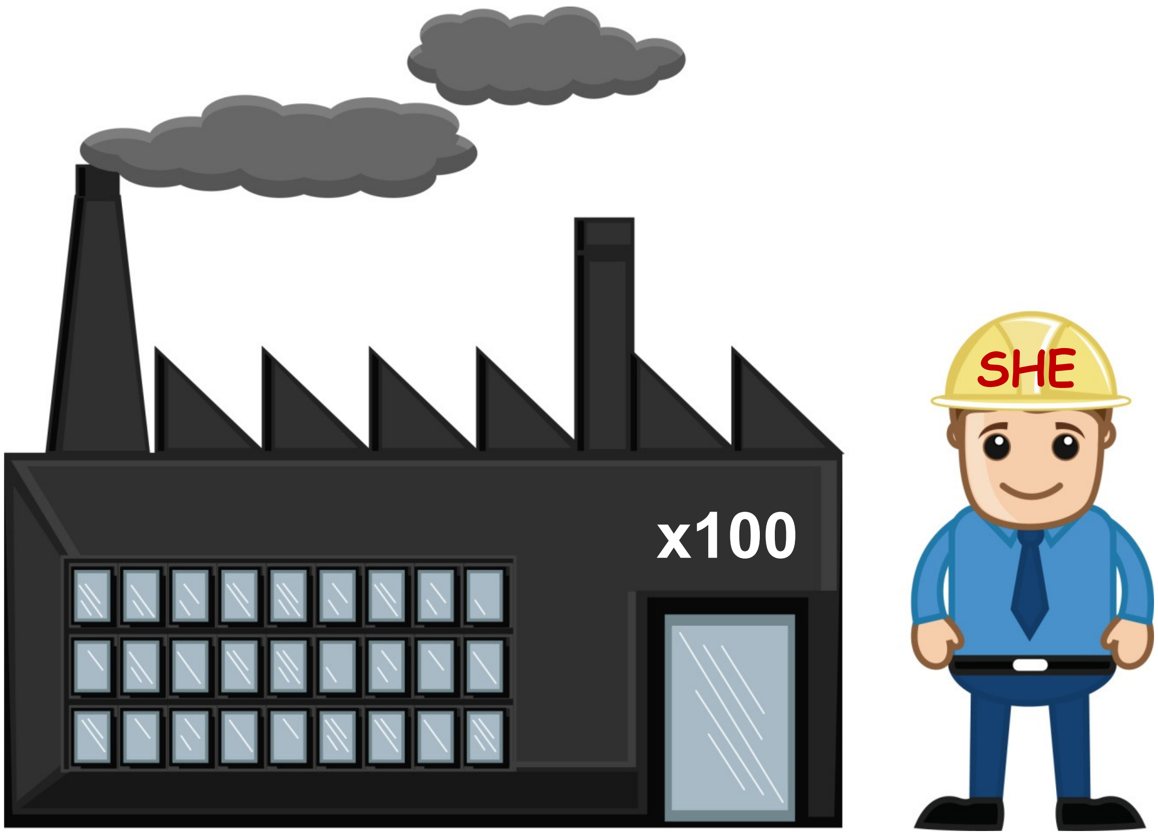
Periodic Table Z=1-138

Calculated in non-relativistic approximation of Dirac - Fok



What's next?

In order to expand the field of research it is necessary first of all to increase the sensitivity of experiments



SHE-Factory

SHE-Factory

joining of efforts

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

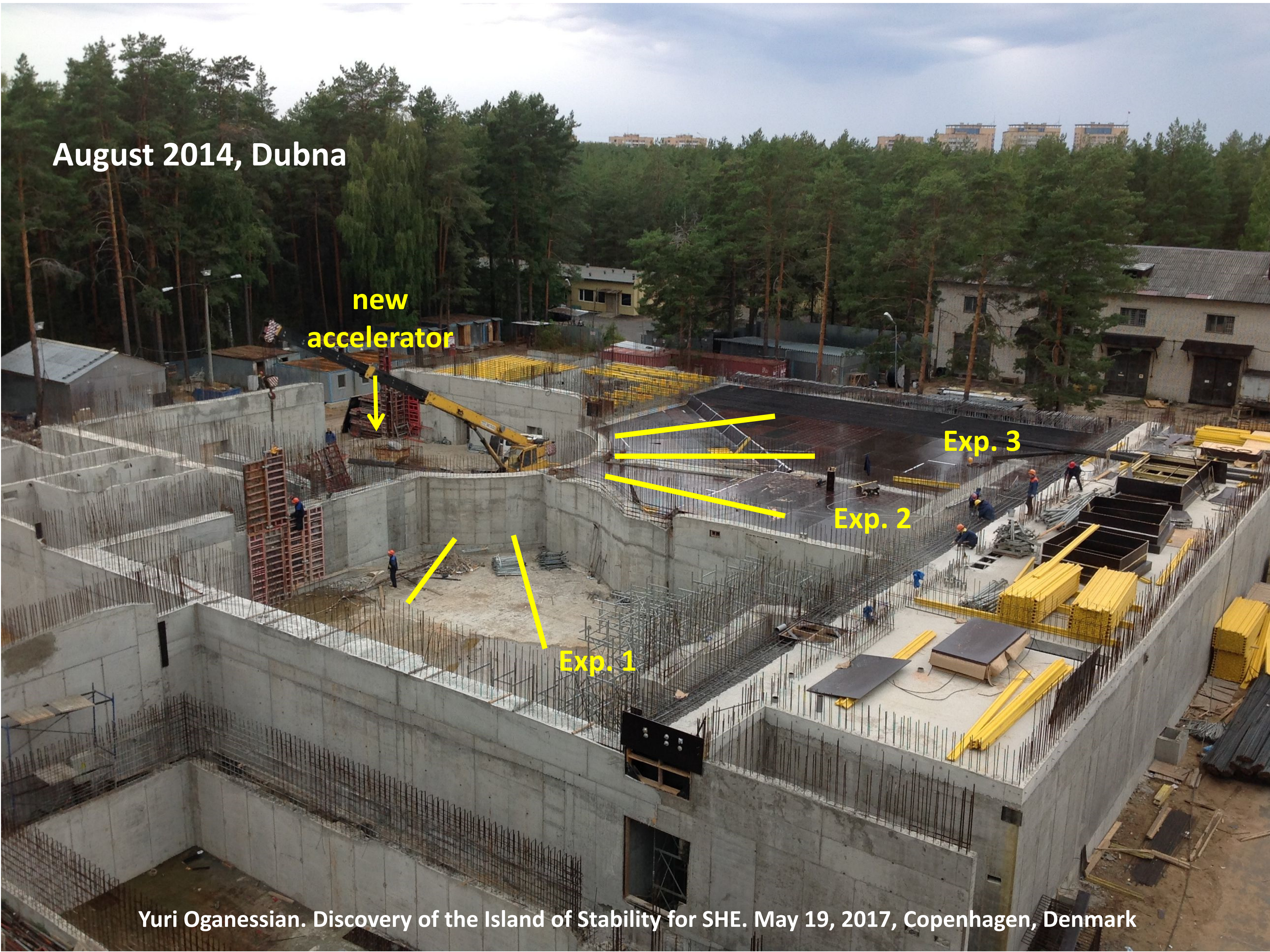
Factor 10-20

Depend of target durability

SC- recoil separator
equipped with
Gas Catcher
On-line separator
& sophisticated
Detectors

Factor 3-5

is closely linked to the intellect


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

Collaboration

Thank you, very much!

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)

Knoxville University (Knoxville, USA)