Moscow State University

Nuclei at the Mass Limit: Discovery of Super Heavy Nuclei

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The seminar on Nuclear Physics of INPh (MSU)
April 04, 2017, Moscow

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..

- All atoms of one element are similar and have the same weight,
- Atoms of different elements have different weights,

John Dalton 1808

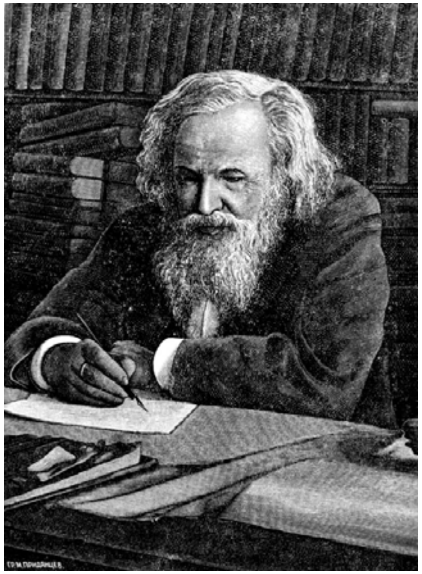
- The building bricks – molecules – are complex compositions of different atoms in certain proportions,
- The matter is neither formed nor is disappearing in chemical reactions

36 elements were known at that time

63 elements were already know by that time

	г р у п п ы э л е м е н т о в										
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

Mendeleev’s Table of elements (1869) showed for the first time

that the chemical properties
(or the nature of the interaction)

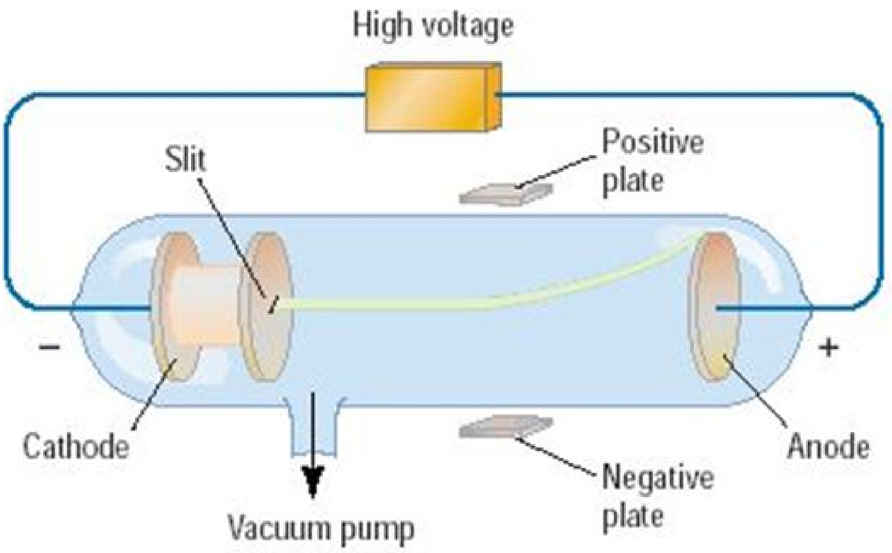
are regularly repeated with increasing the weight (or atomic number) of the elements.

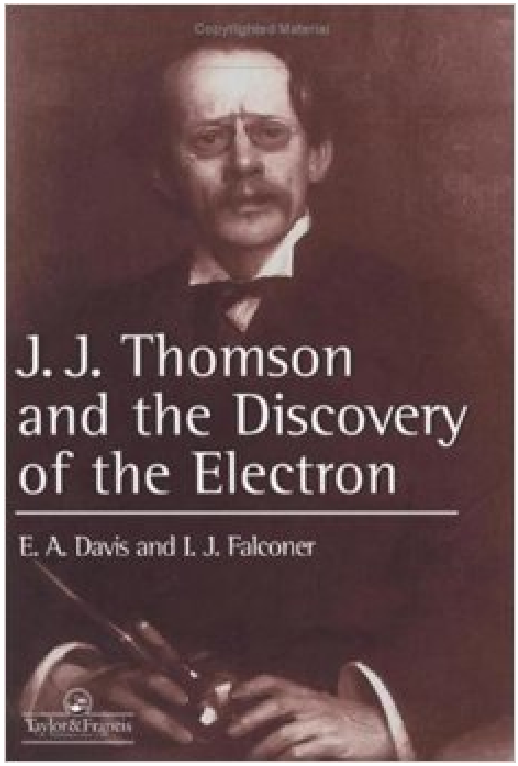
It follows that:
the atoms are not "building bricks",

They themselves are complex internal structures.

Discovery of the Electron

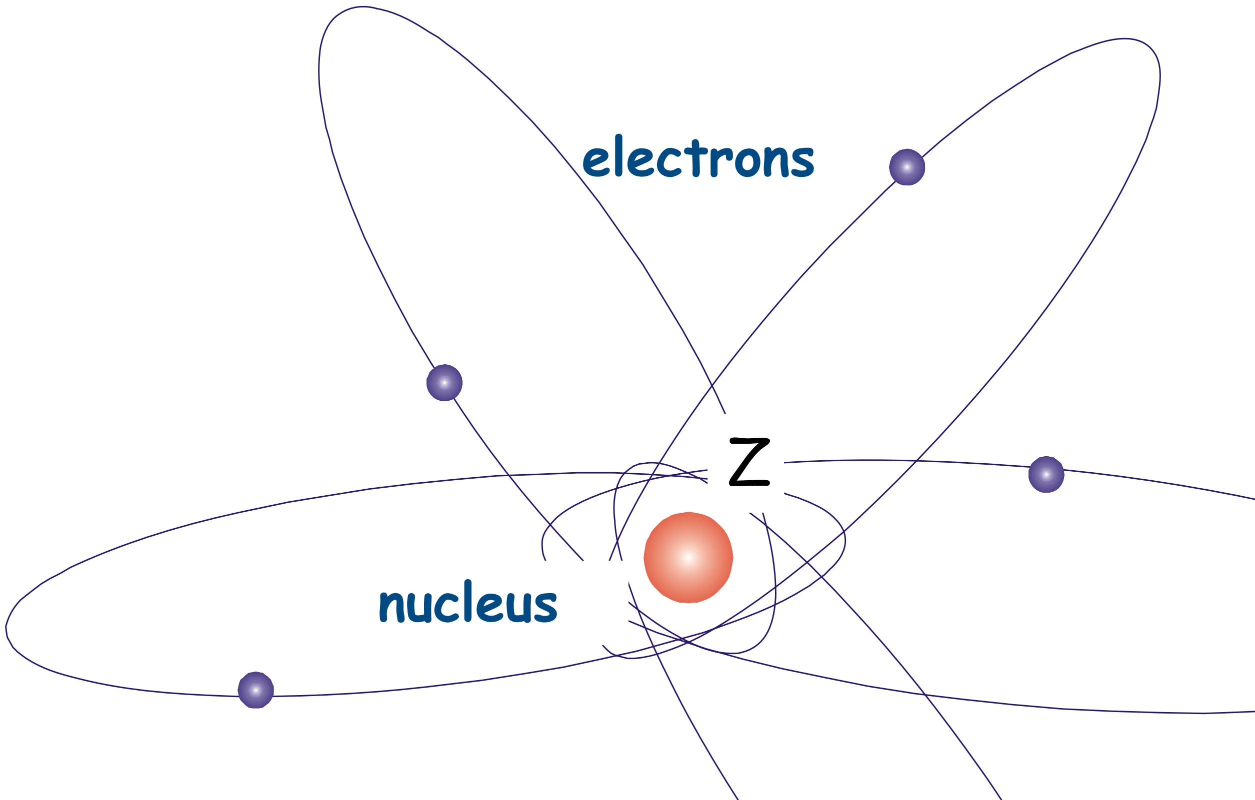
In 1897, J.J. Thomson used a cathode ray tube to deduce the presence of a negatively charged particle.

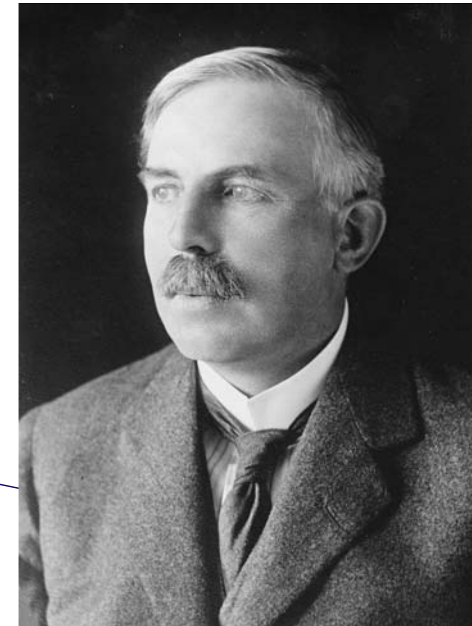




Cathode ray tubes pass electricity through a gas that is contained at a very low pressure.

86 elements were already known by that time





Ernest Rutherford
March7, 1911

Planetary model of atom

It became clear that existence of atom is limited by stability of its nucleus.

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.

With this beautiful macroscopic and, in this sense, classical model of nucleus that presents nuclei as drops of charged liquid of constant density:

G.A.Gamov –developed the theory of alpha-decay of the atomic nuclei (1928)

C.F. von Weizsäcker – wrote the famous formula for the binding energy of nuclei (1933)

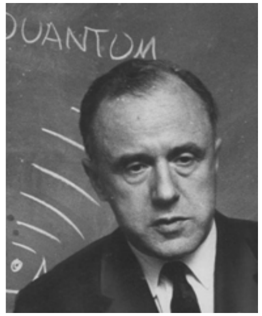
N.Bohr and J.Wheeler – developed the theory of nuclear fission (1939)

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?

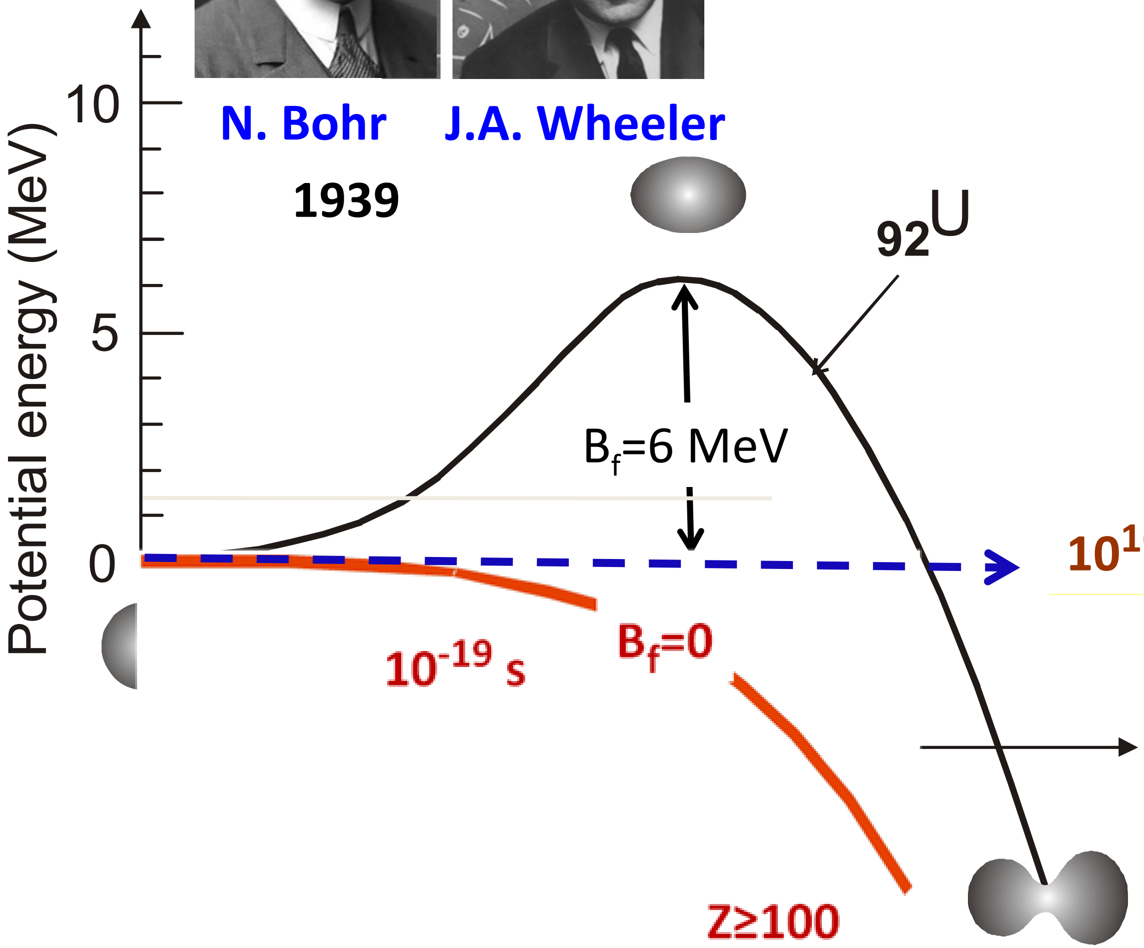
Nuclear fission

N. Bohr



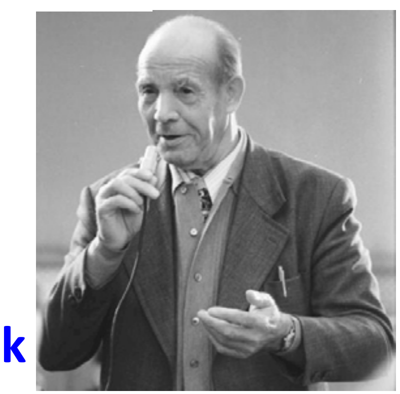
J.A. Wheeler

1939



G.N. Flerov

1940



K.A. Petrzhak

Chart of the Nuclides

SF

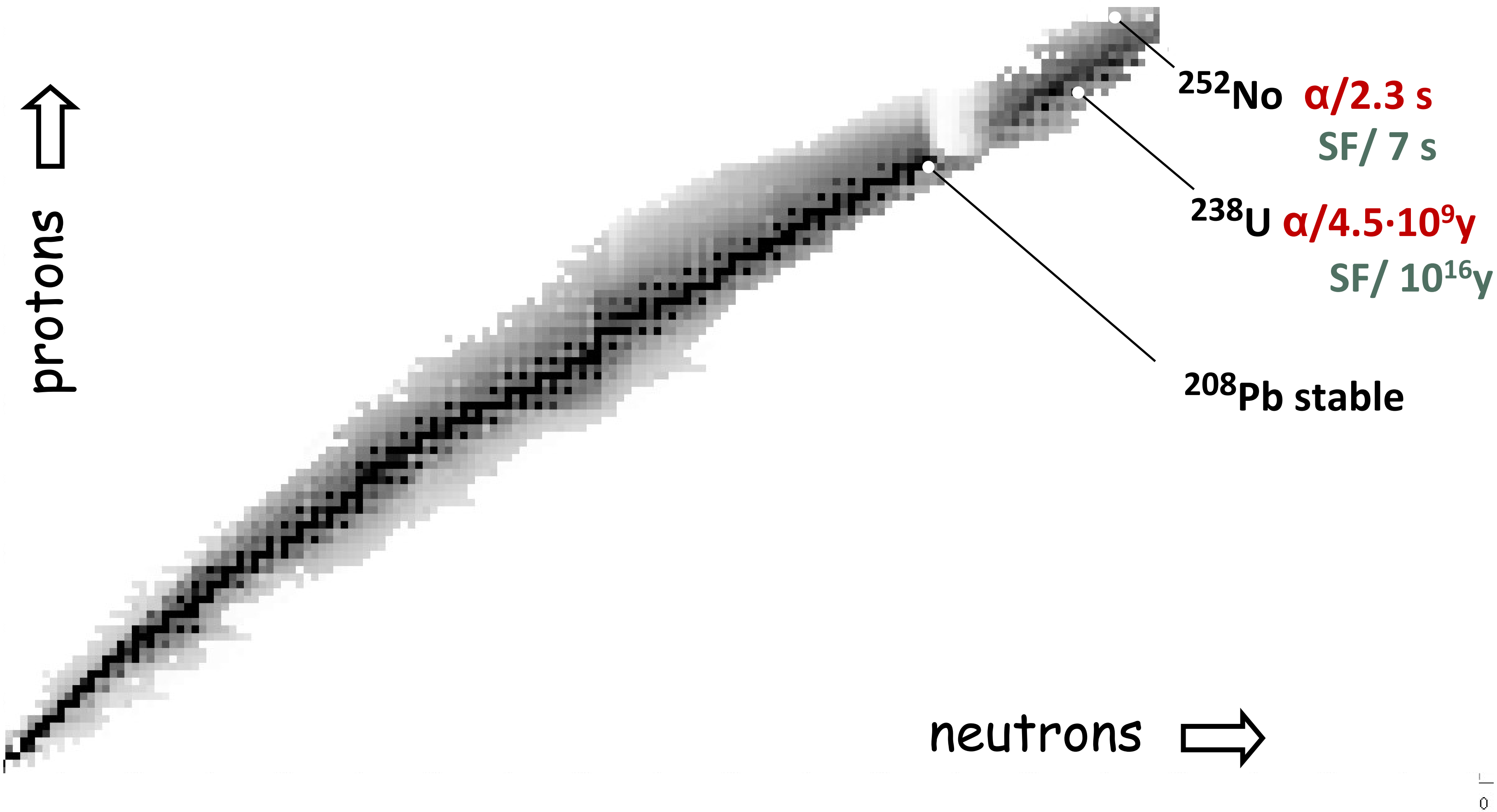
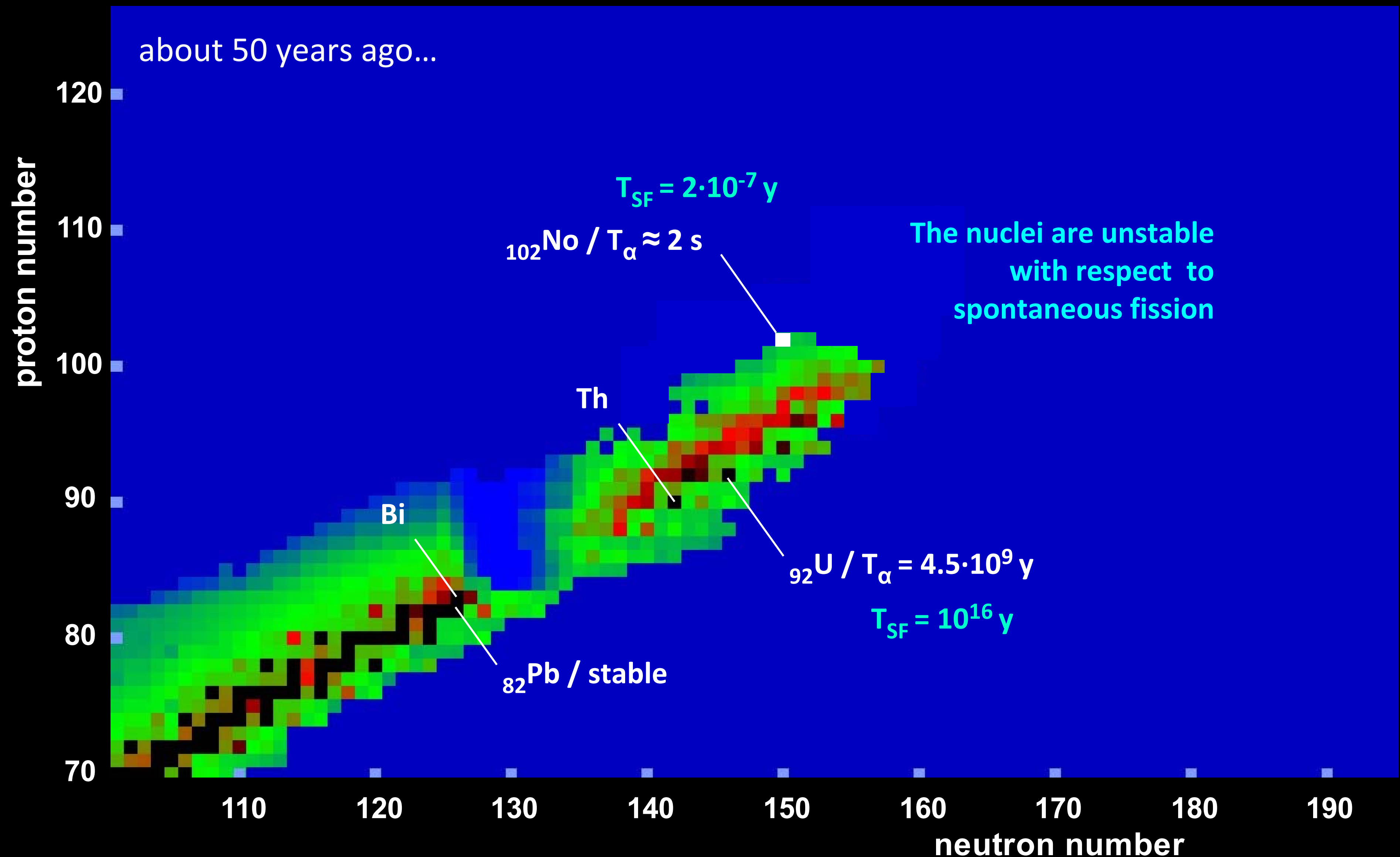


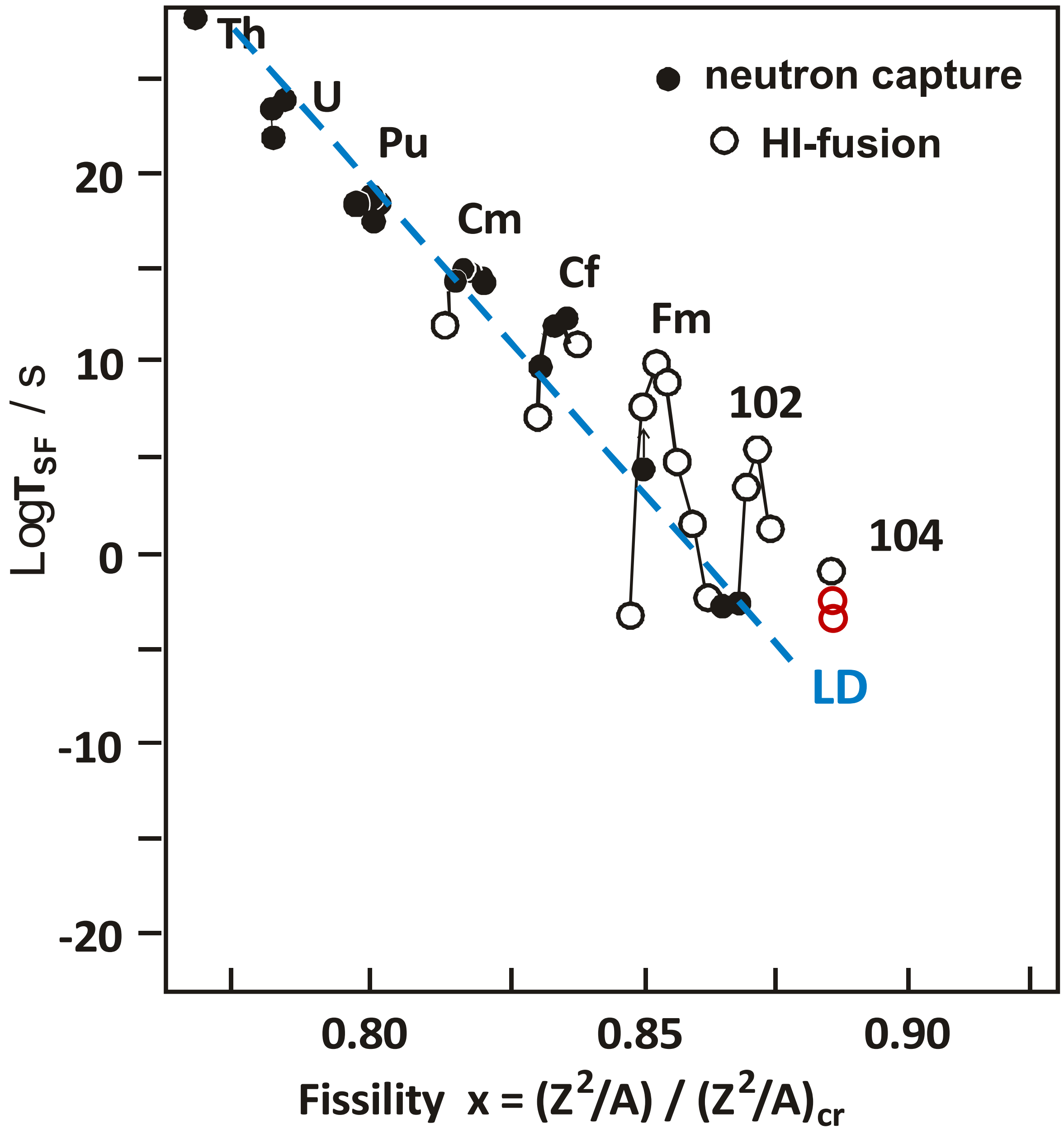
Chart of nuclides

Macroscopic theory (Liquid Drop Model)



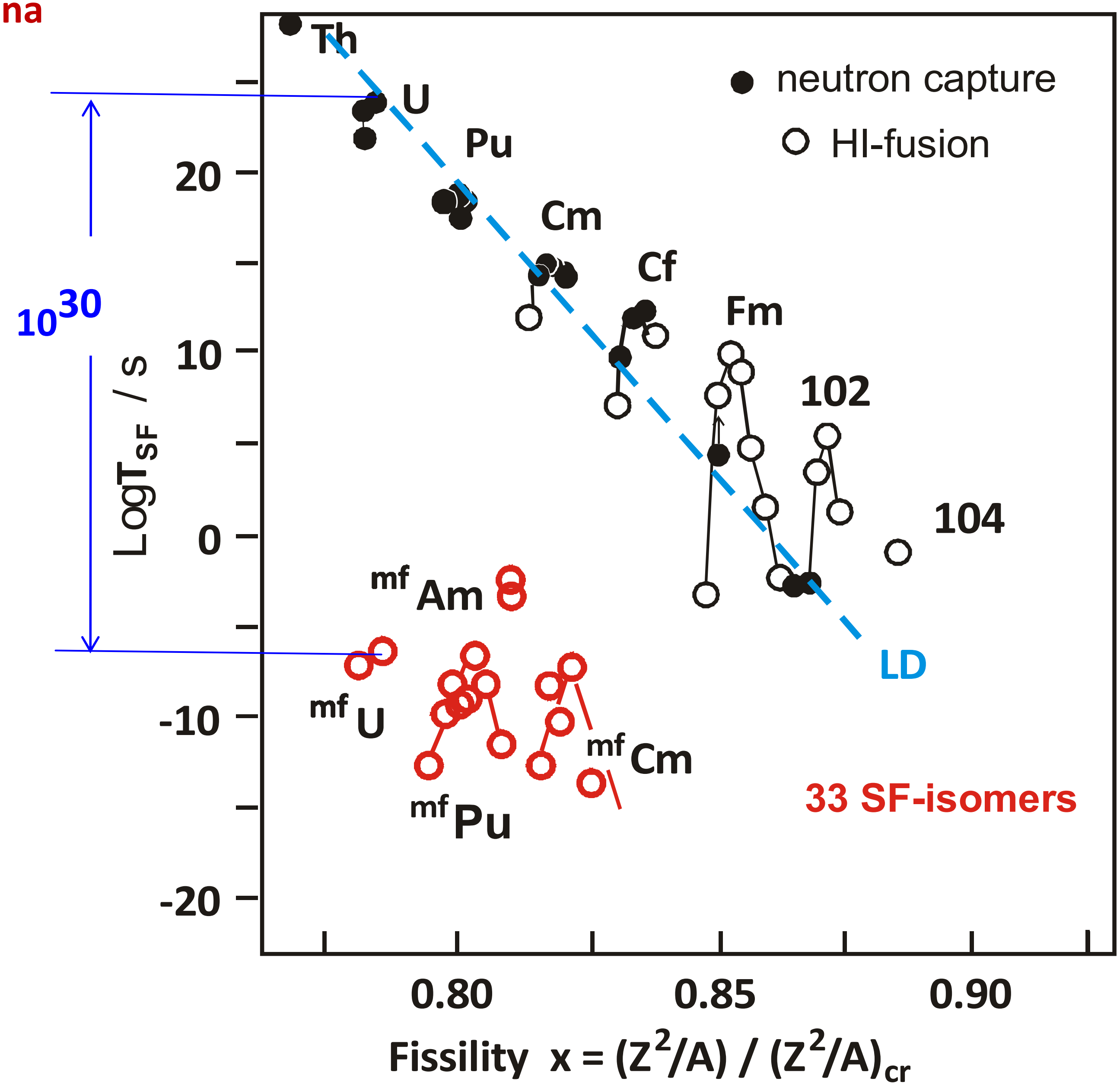
1962 JINR, Dubna

Search for Element 104 in $^{242}Pu + ^{22}Ne$ reaction



Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

1962 JINR, Dubna

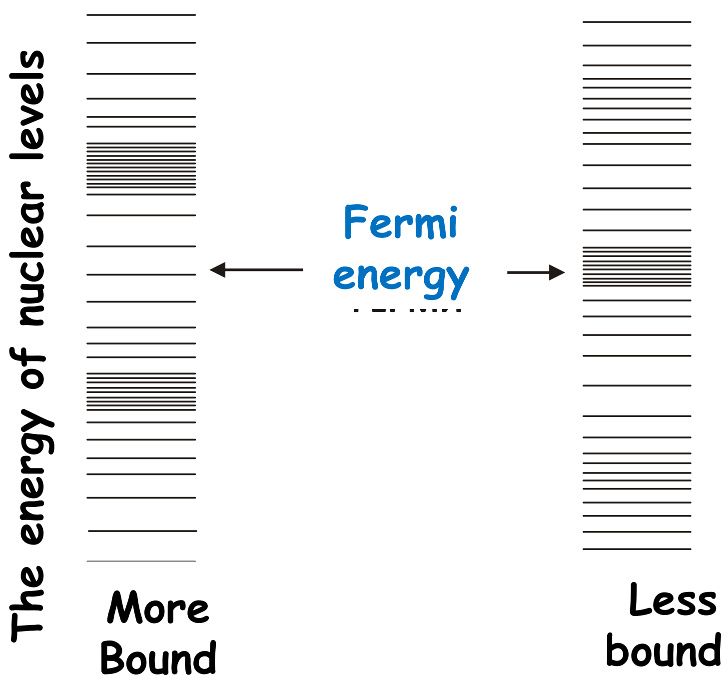


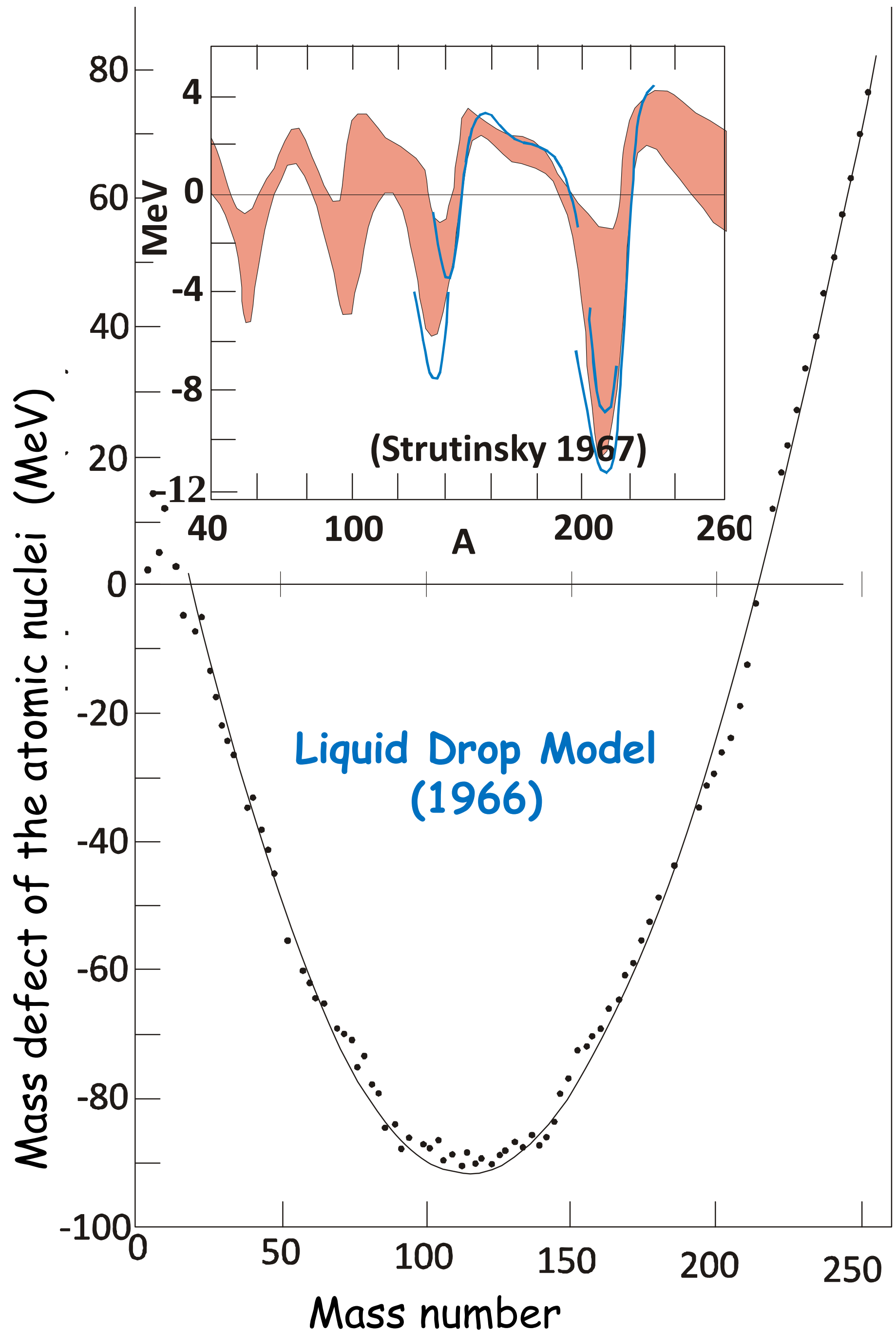
Nuclear structure

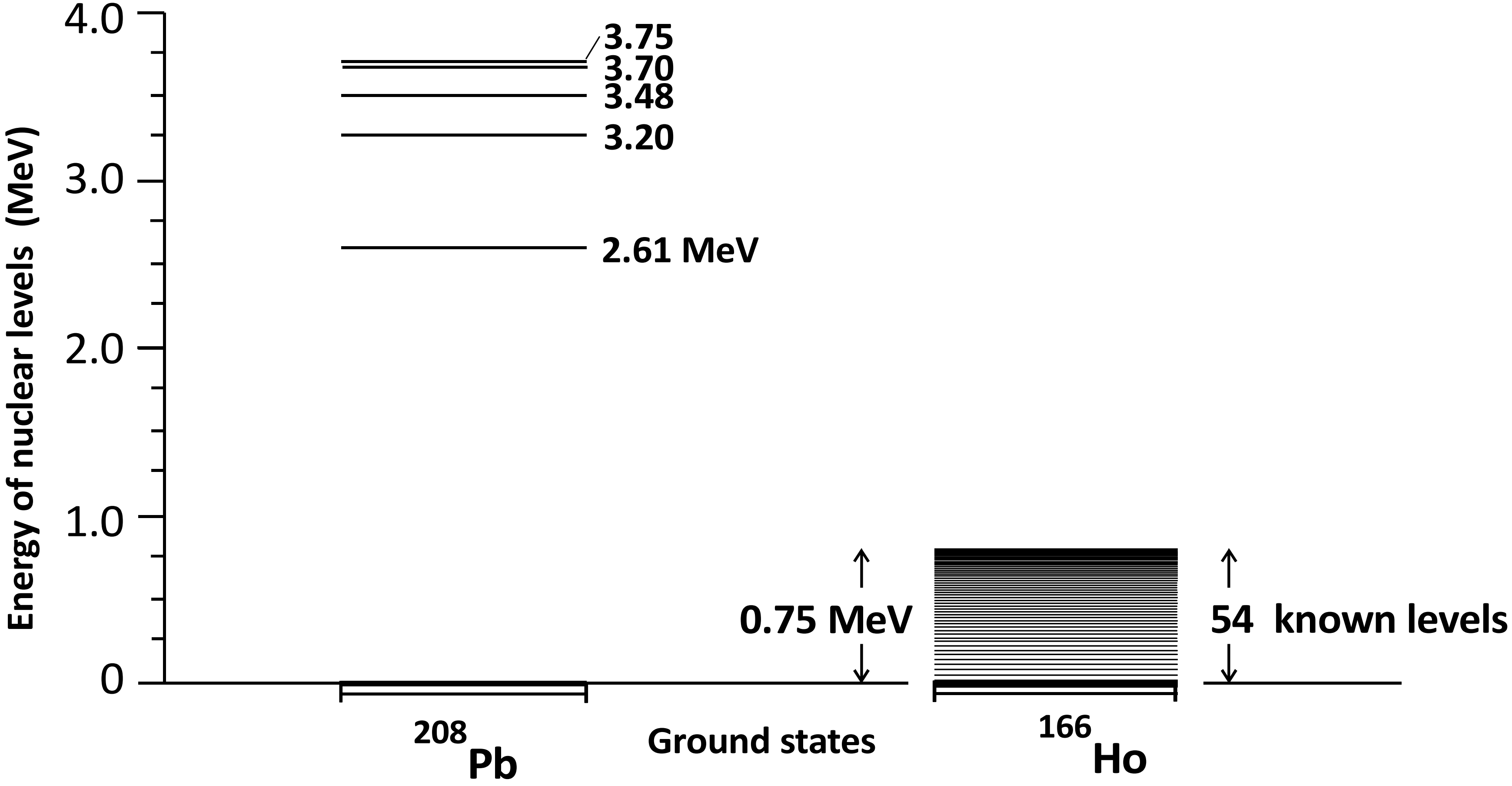
and stability of the heaviest nuclei

Nuclear Shells

Shell correction





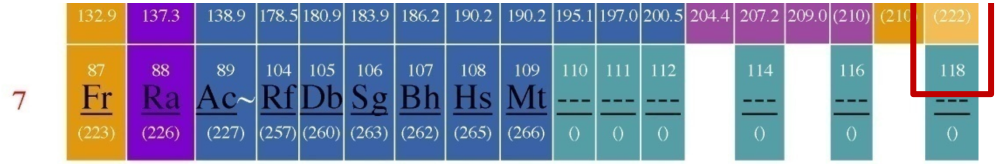

Energy of nuclear levels (MeV)
4.0
3.0
2.0
1.0
0
3.75
3.70
3.48
3.20
2.61 MeV
0.75 MeV
54 known levels
208 Pb
Ground states
166 Ho

In this interpretation, the manifestation of the nuclear structure is similar to the effect of the electron shells closure in the atoms,– **${}_{2}He$, ${}_{10}Ne$, ${}_{18}Ar$, ${}_{54}Xe$, ${}_{86}Rn$** known as “noble gases” located in the last column of the Table of Elements.

Maybe that's why the appearance of this effect in the nucleus has been called **nuclear shells closure ....**

However the analogy is very conditional because of a very dense nuclear matter can not have the structure of the atom

(remember the model of atom of Rutherford – Bohr)

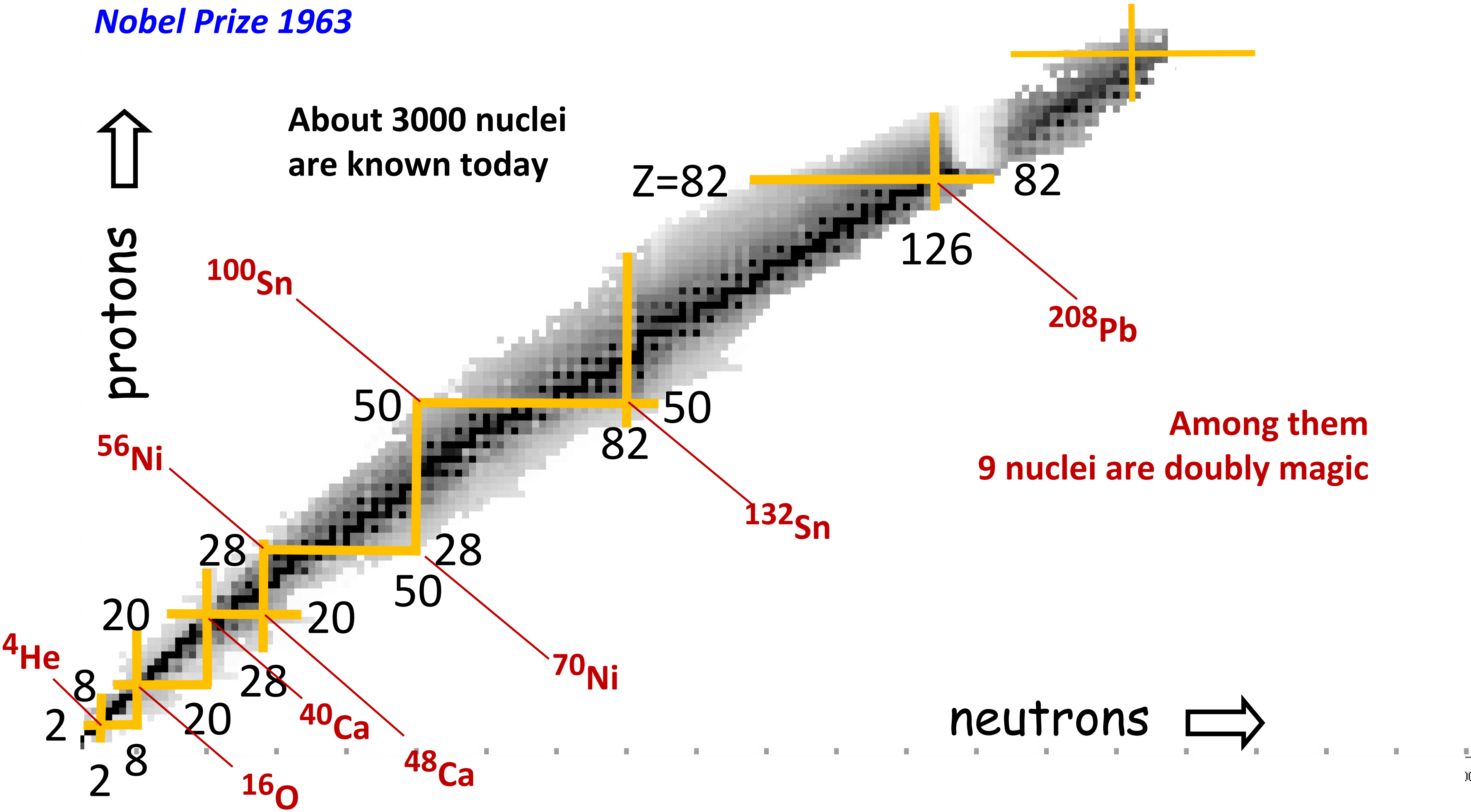


Shell and magic numbers

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

NEW SHELLS ?

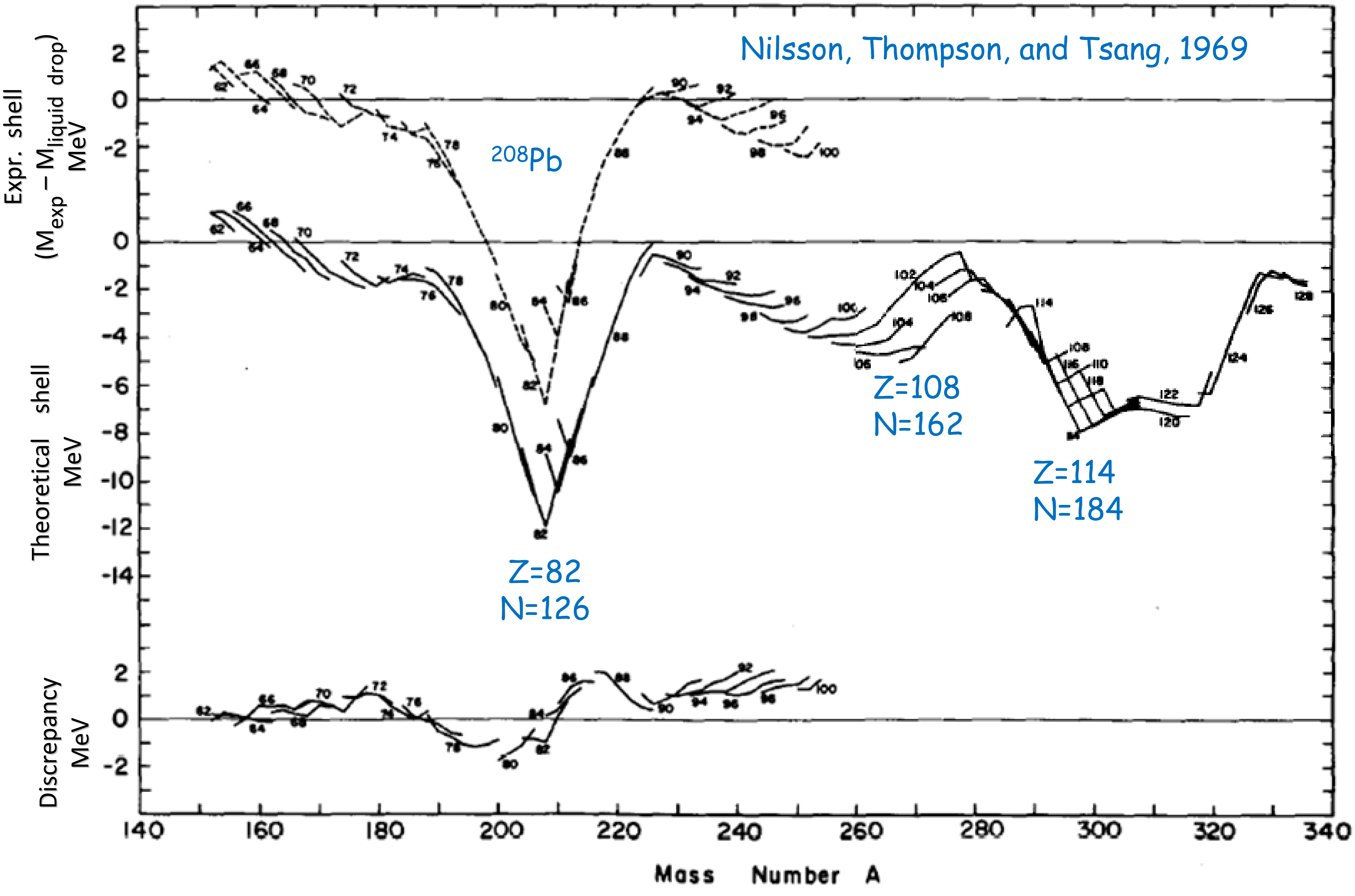
About 3000 nuclei are known today



Among them
9 nuclei are doubly magic

Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

Shell effect in the nuclear ground states (mass defect)



Proton and neutron single particle energy spectra calculated for deform $^{270}108$ and $^{298}114$ doubly magic nuclei

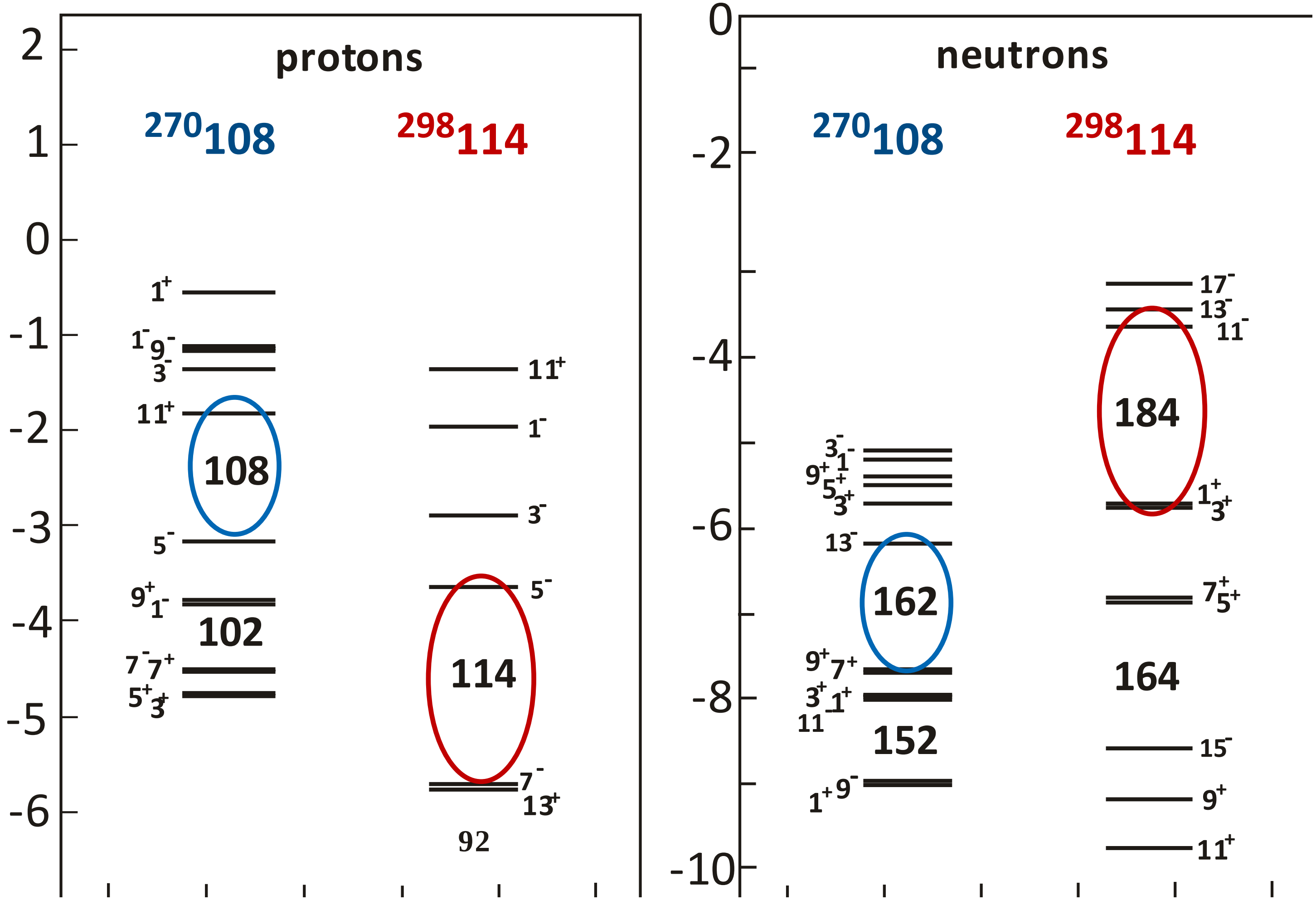
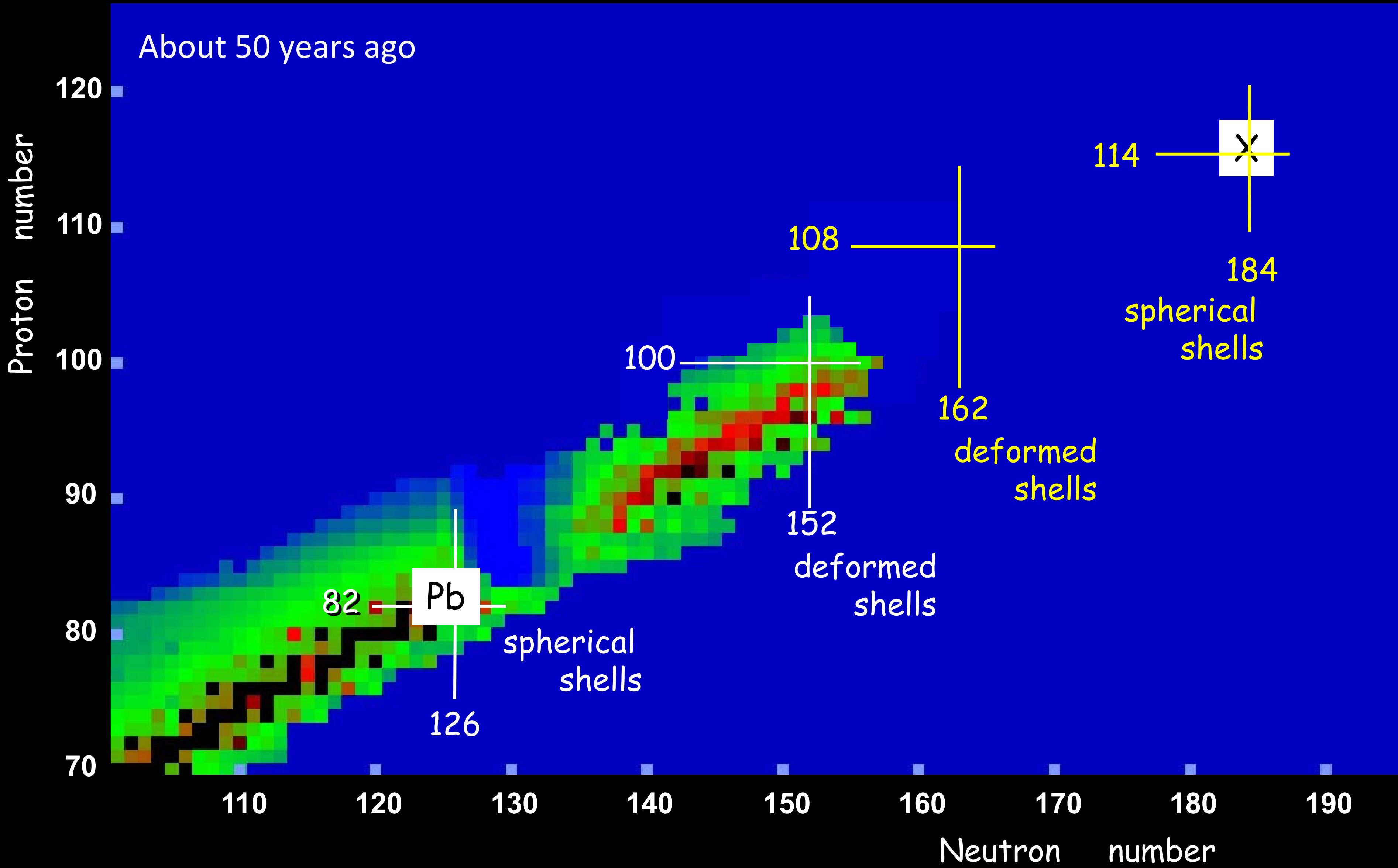
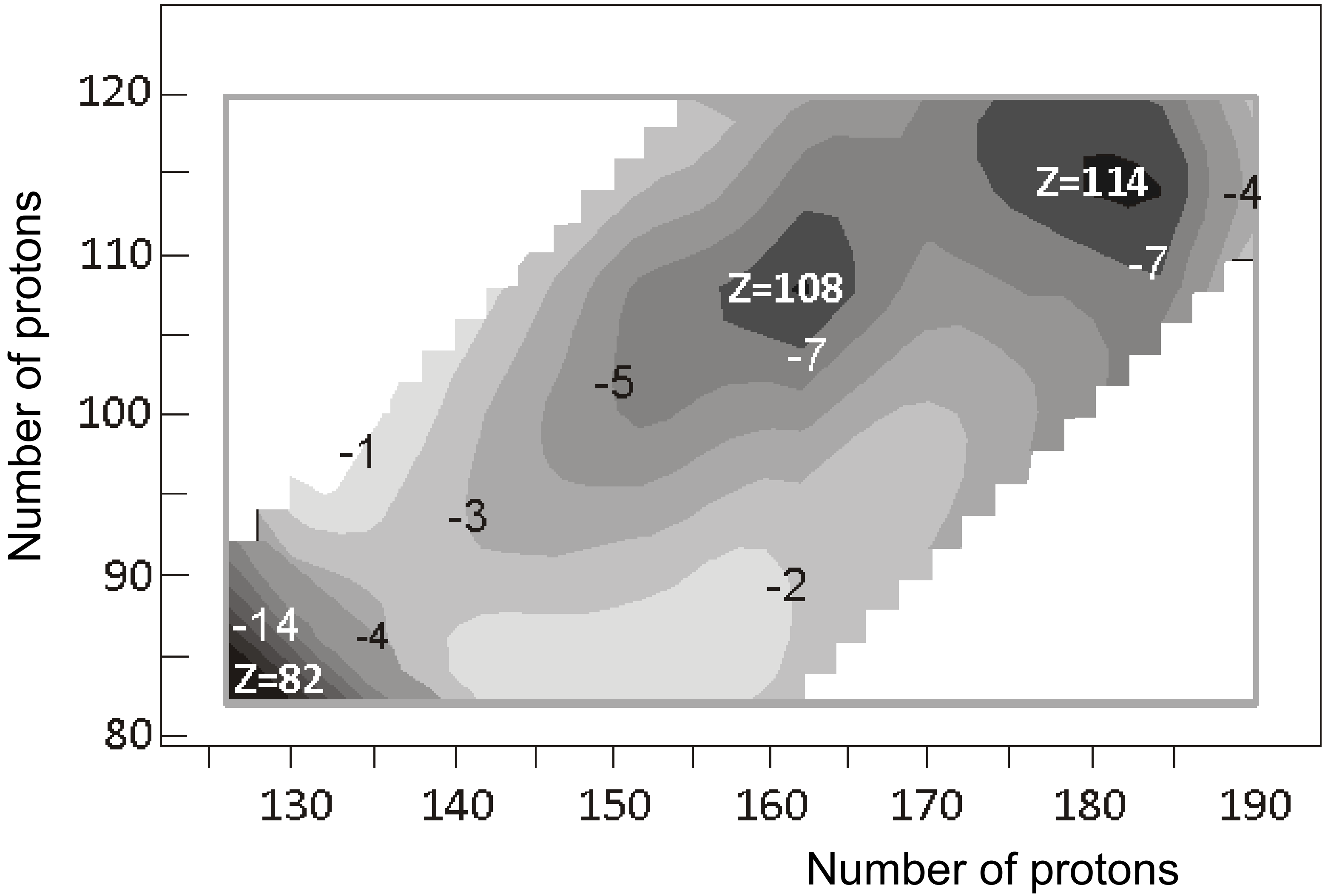


Chart of nuclides

Nuclear shells
(macro-microscopic calculations)

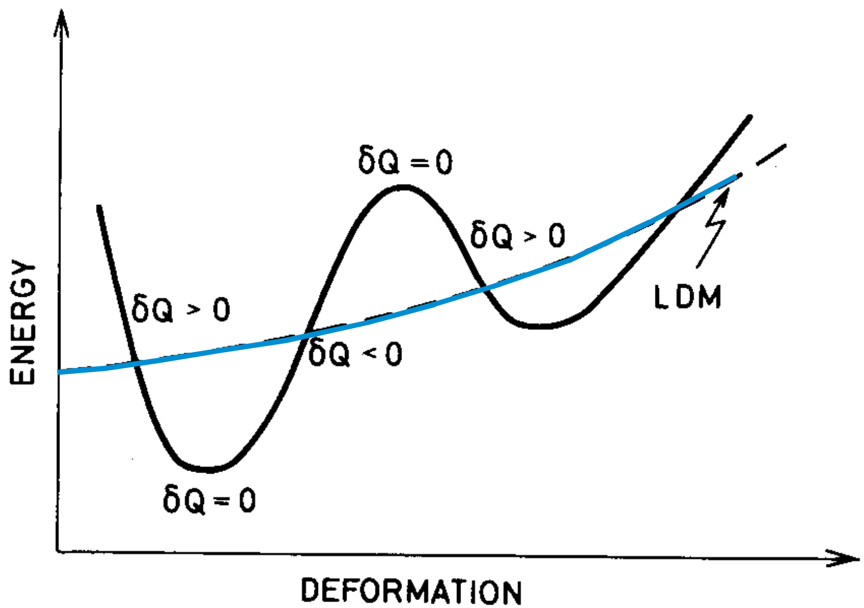


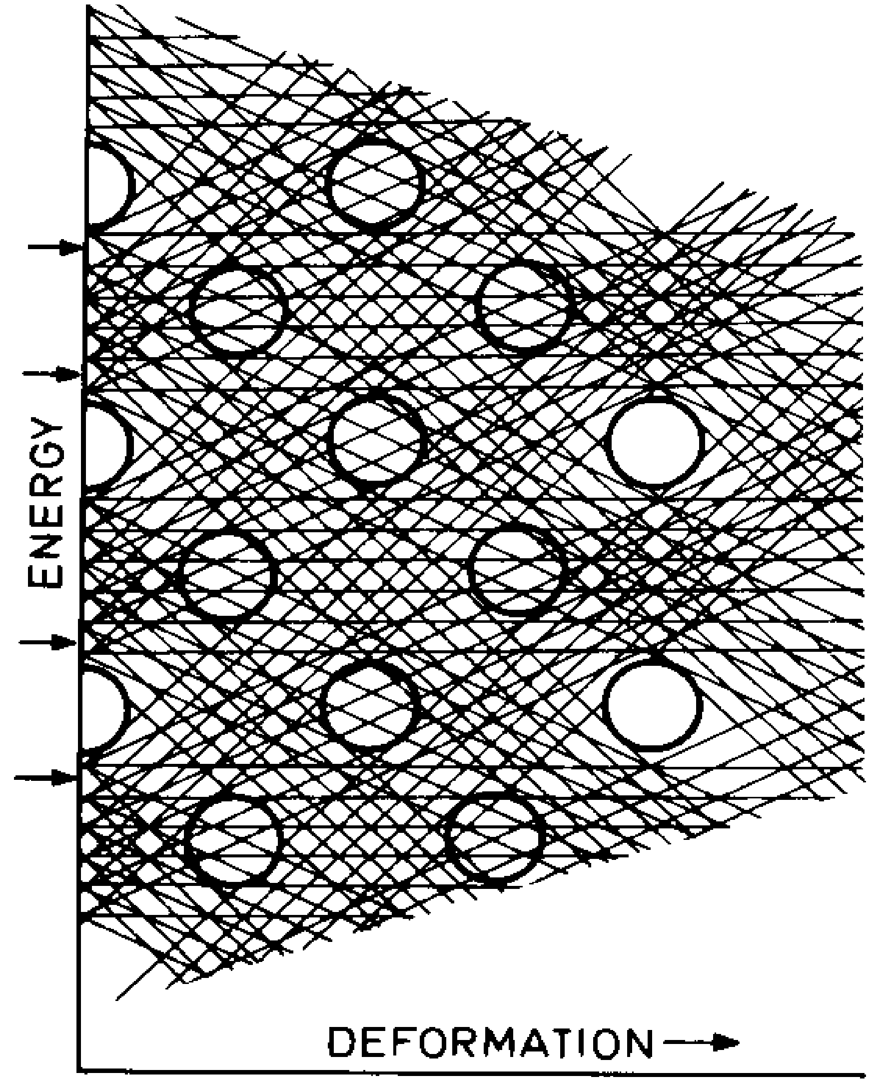
Map of the shell corrections (in MeV) to the liquid drop potential energy

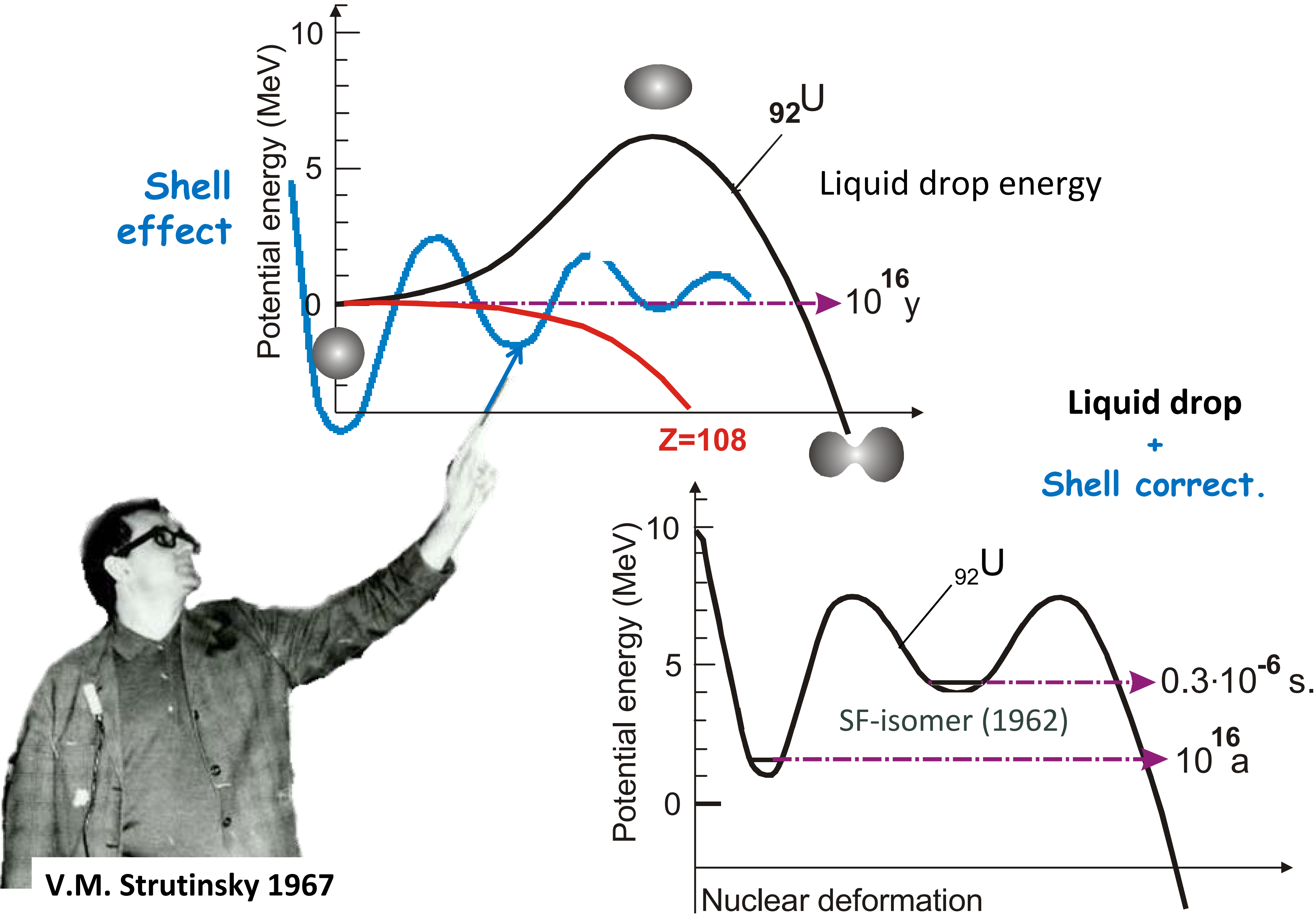


Shell effect with increasing of nuclear deformation

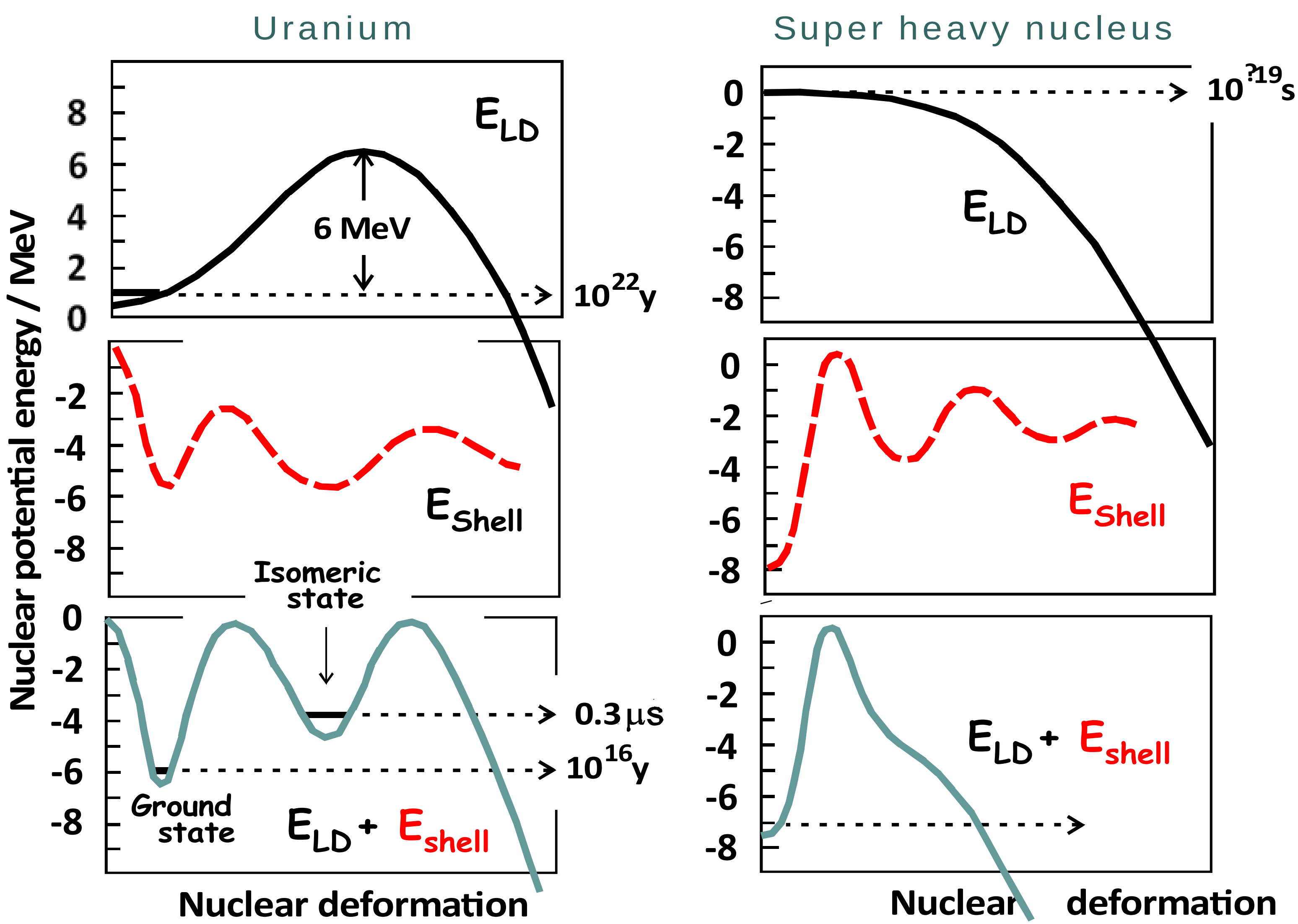
Nuclear levels depending on deformation





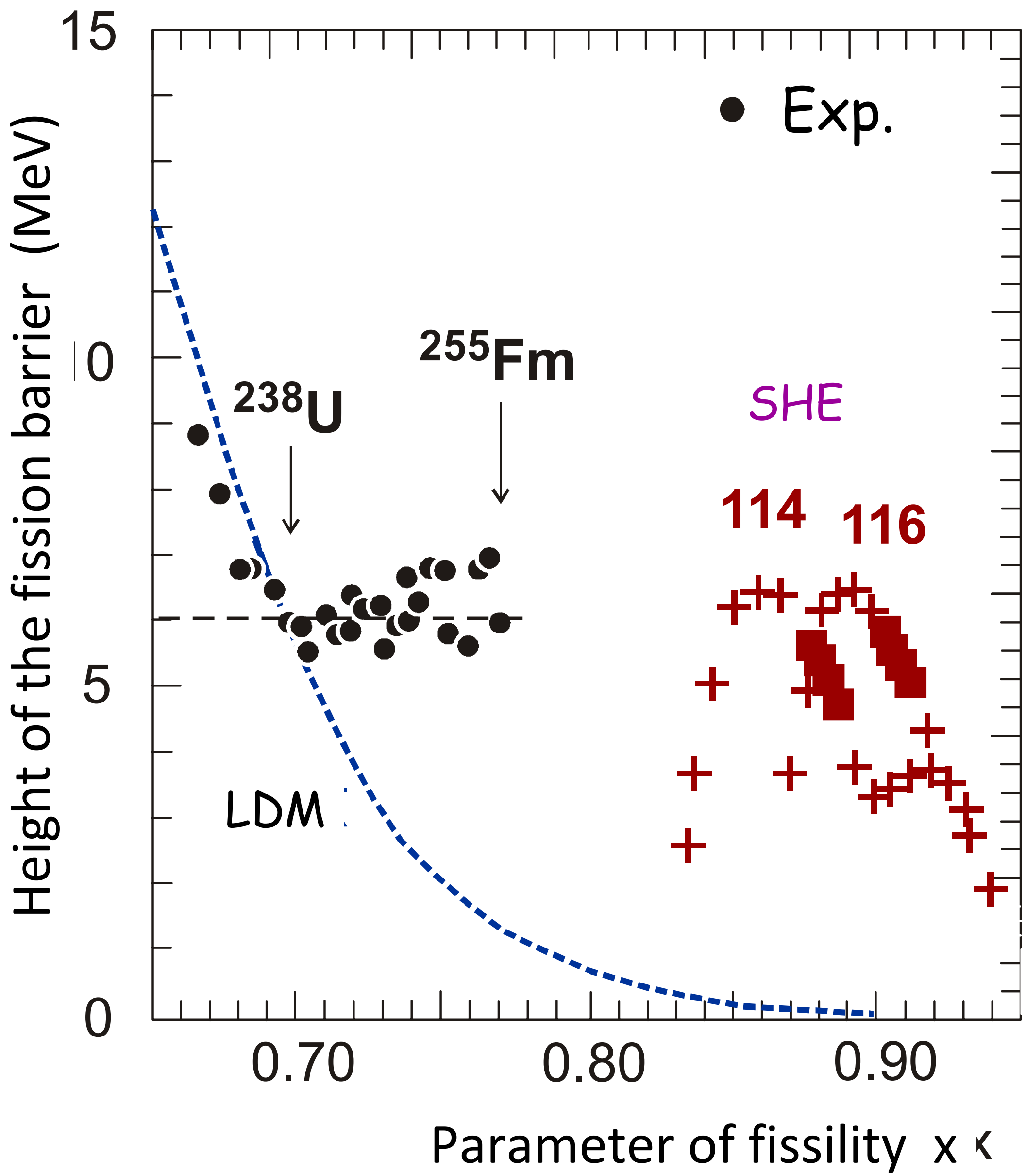


Shell effect
Potential energy (MeV)
10
5
0
$_{92}$U
Liquid drop energy
10^{16} y
Z=108
Liquid drop
+
Shell correct.
Potential energy (MeV)
10
5
0
$_{92}$U
$0.3 \cdot 10^{-6}$ s.
SF-isomer (1962)
10^{16} a
Nuclear deformation
V.M. Strutinsky 1967



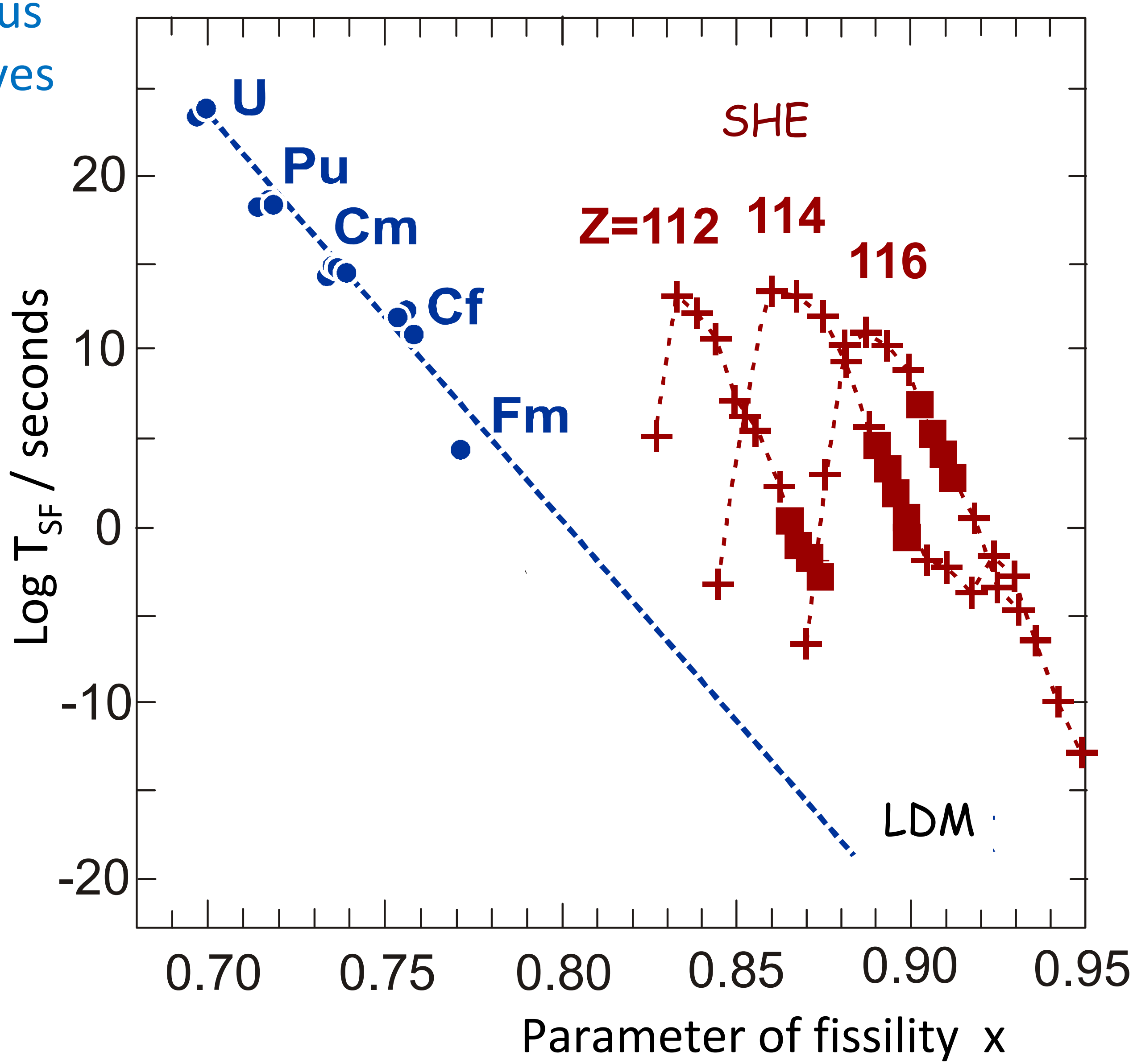
Yu. Oganessian. “Nuclear at the Mass Limit, Discovery of SHN” Seminar on NP of INPh April 4, 2017, MSU, Moscow

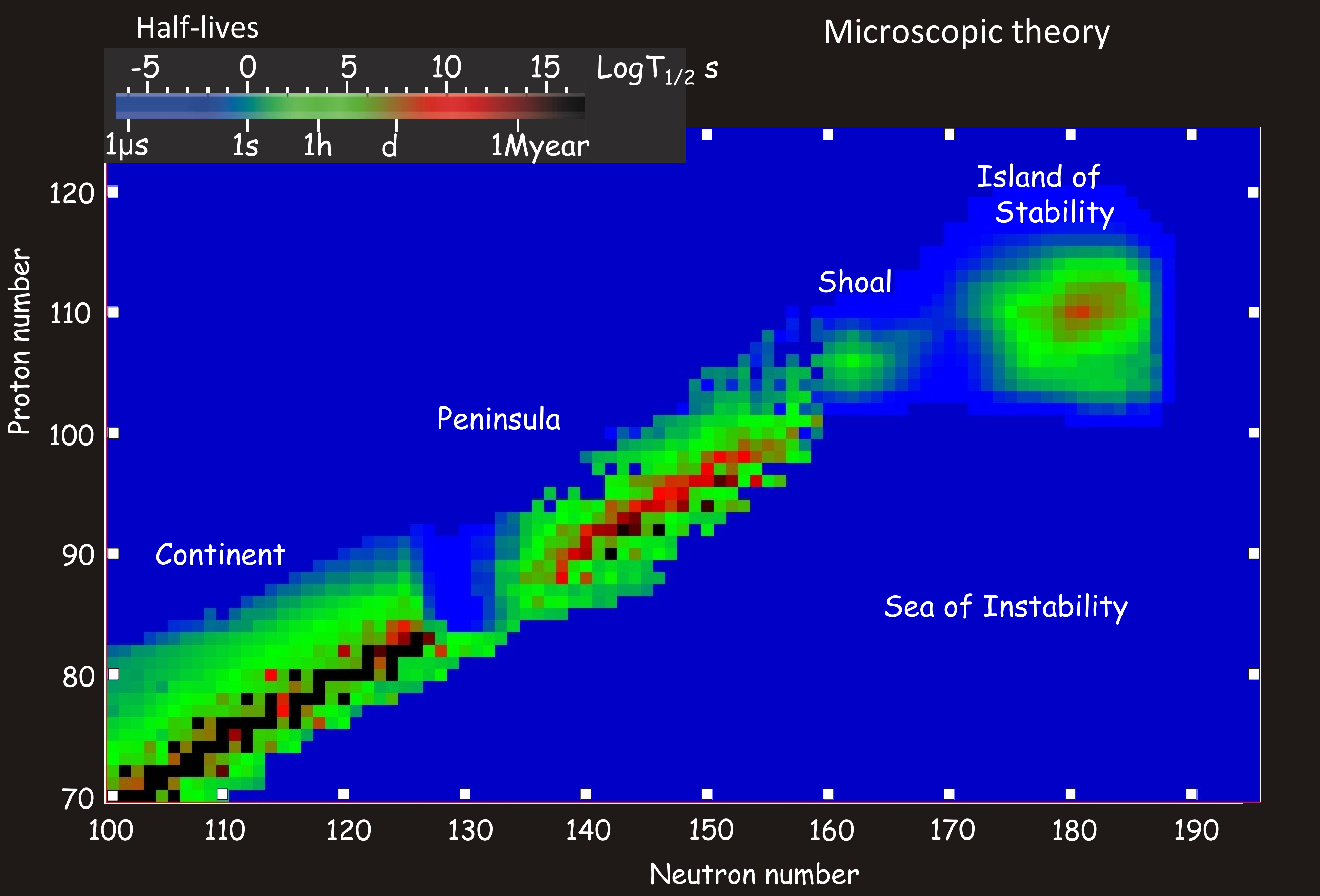
Fission barriers



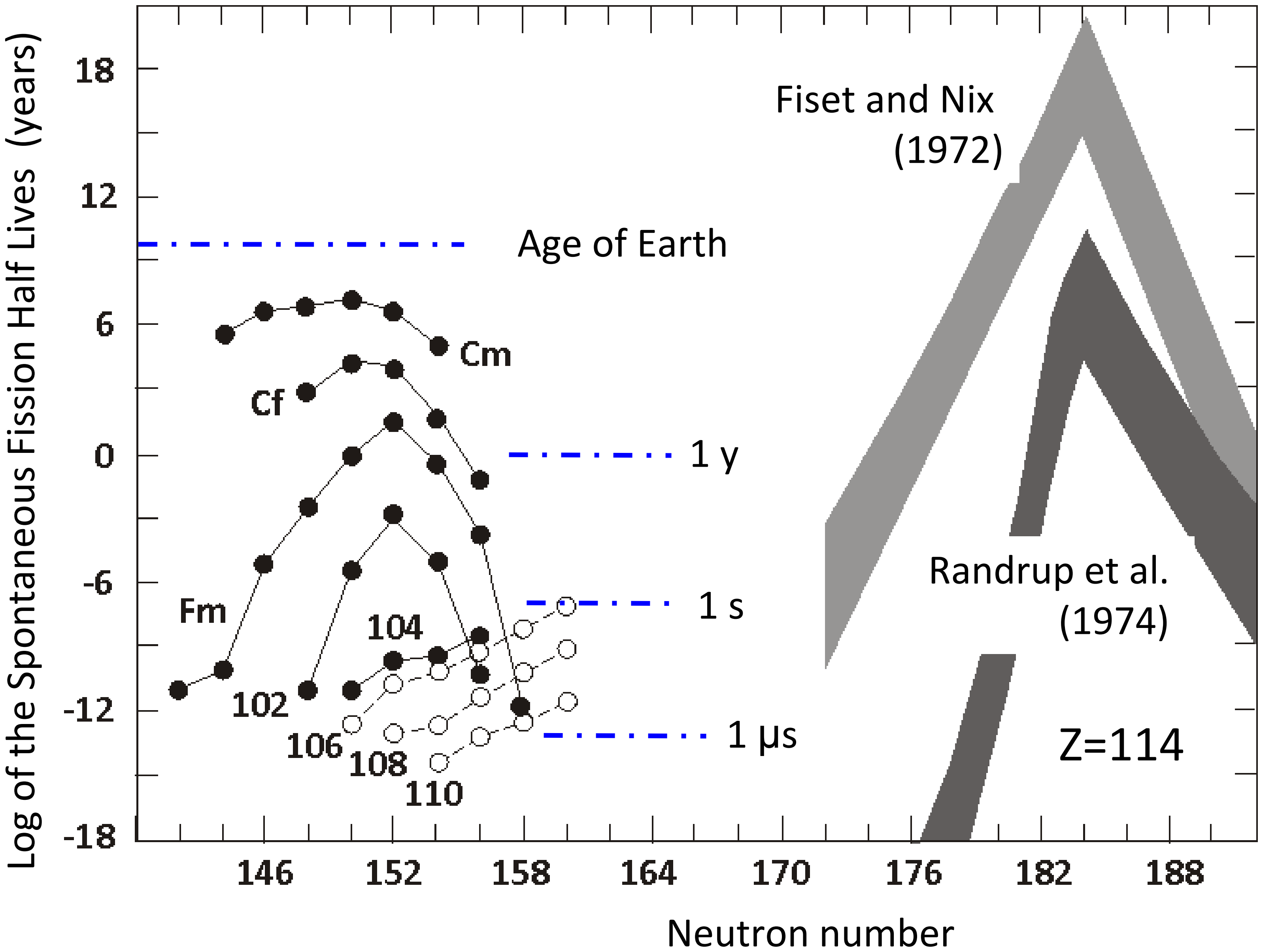
R. Smolańczuk, Phys. Rev. C 56 (1997) 812

Partial Spontaneous Fission Half-Lives





Microscopic theory
Half-lives
-5 0 5 10 15 LogT1/2 s
1μs 1s 1h d 1Myear
Island of Stability
Shoal
Peninsula
Continent
Sea of Instability
Proton number
120 110 100 90 80 70
Neutron number
100 110 120 130 140 150 160 170 180 190



Yu. Oganessian. “Nuclear at the Mass Limit, Discovery of SHN” Seminar on NP of INPh April 4, 2017, MSU, Moscow

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 of every laboratory 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,

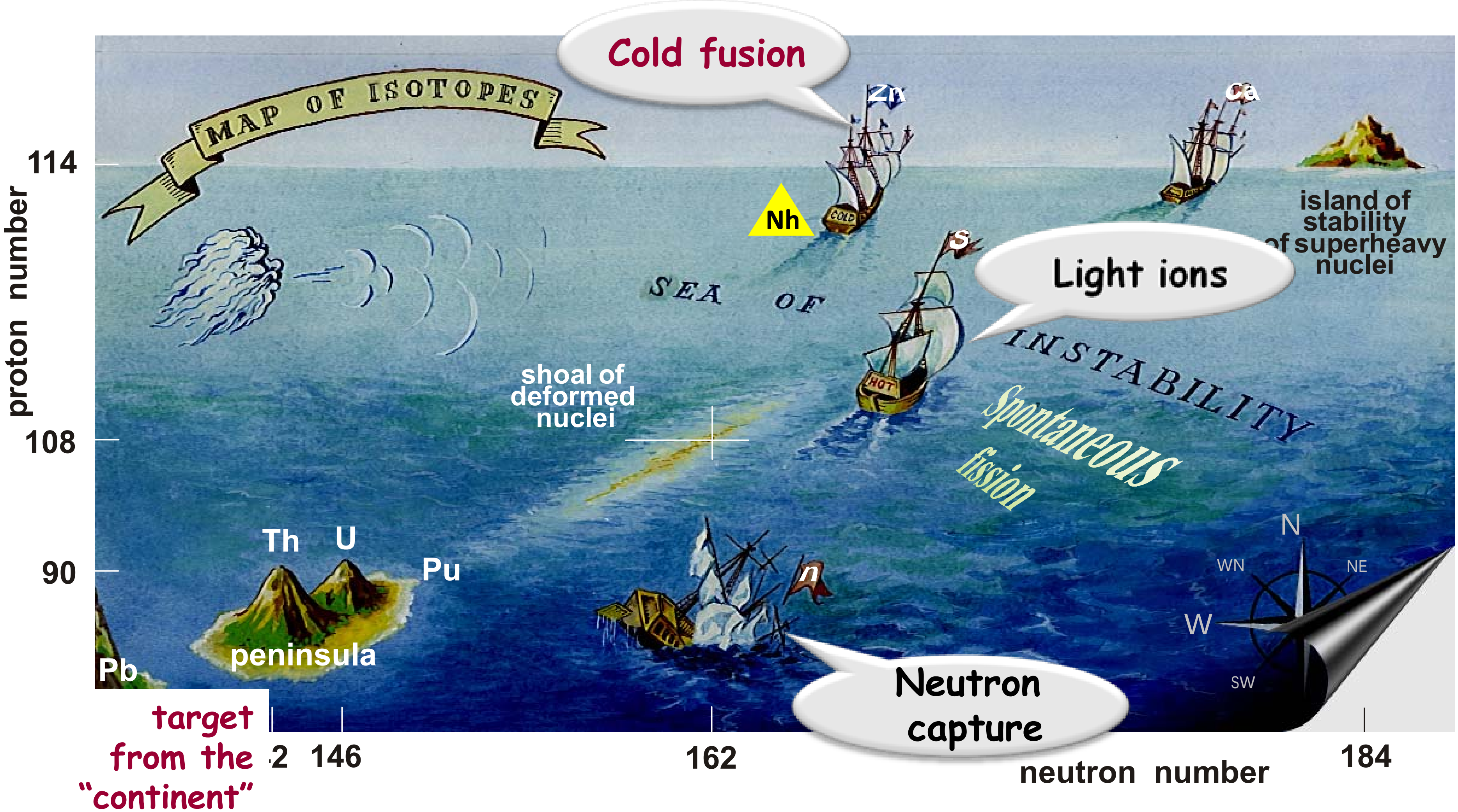
To develop setups and detectors for separating and registering the rarest events of formation and decay of superheavy nuclei

separator/detector, spectrometer, chemical methods, etc.

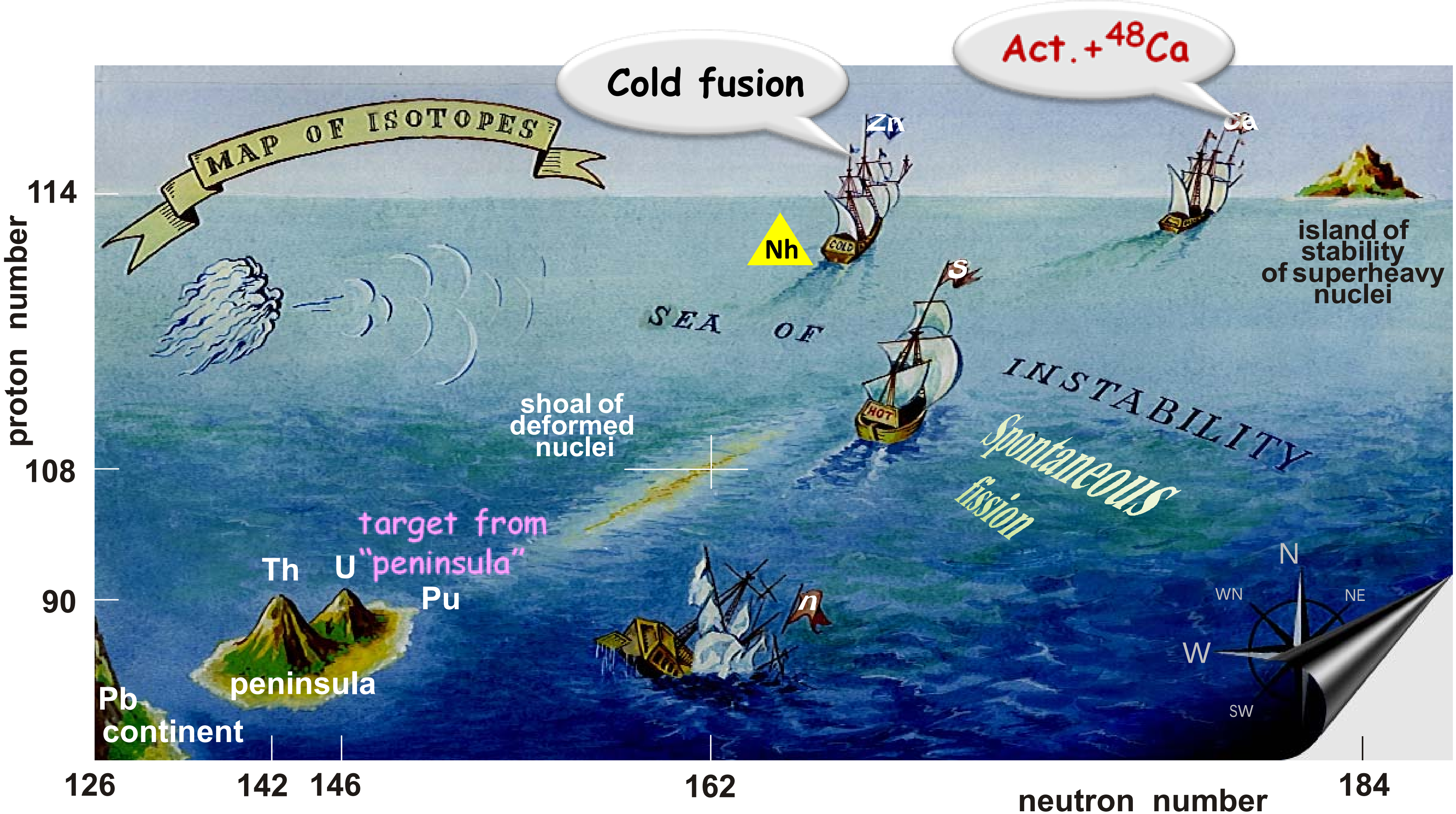
To have much patience

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

Reactions of synthesis

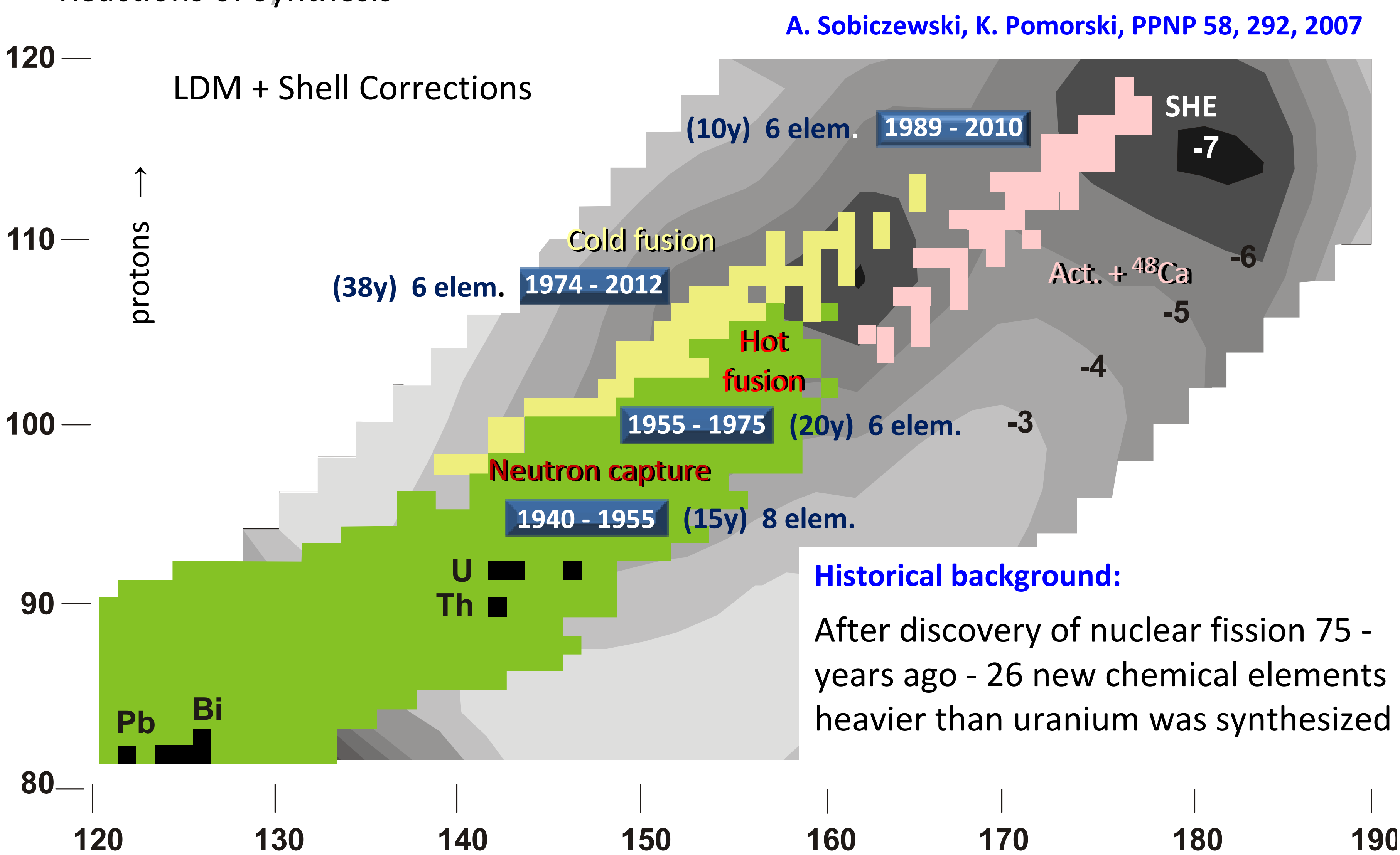


Reactions of synthesis



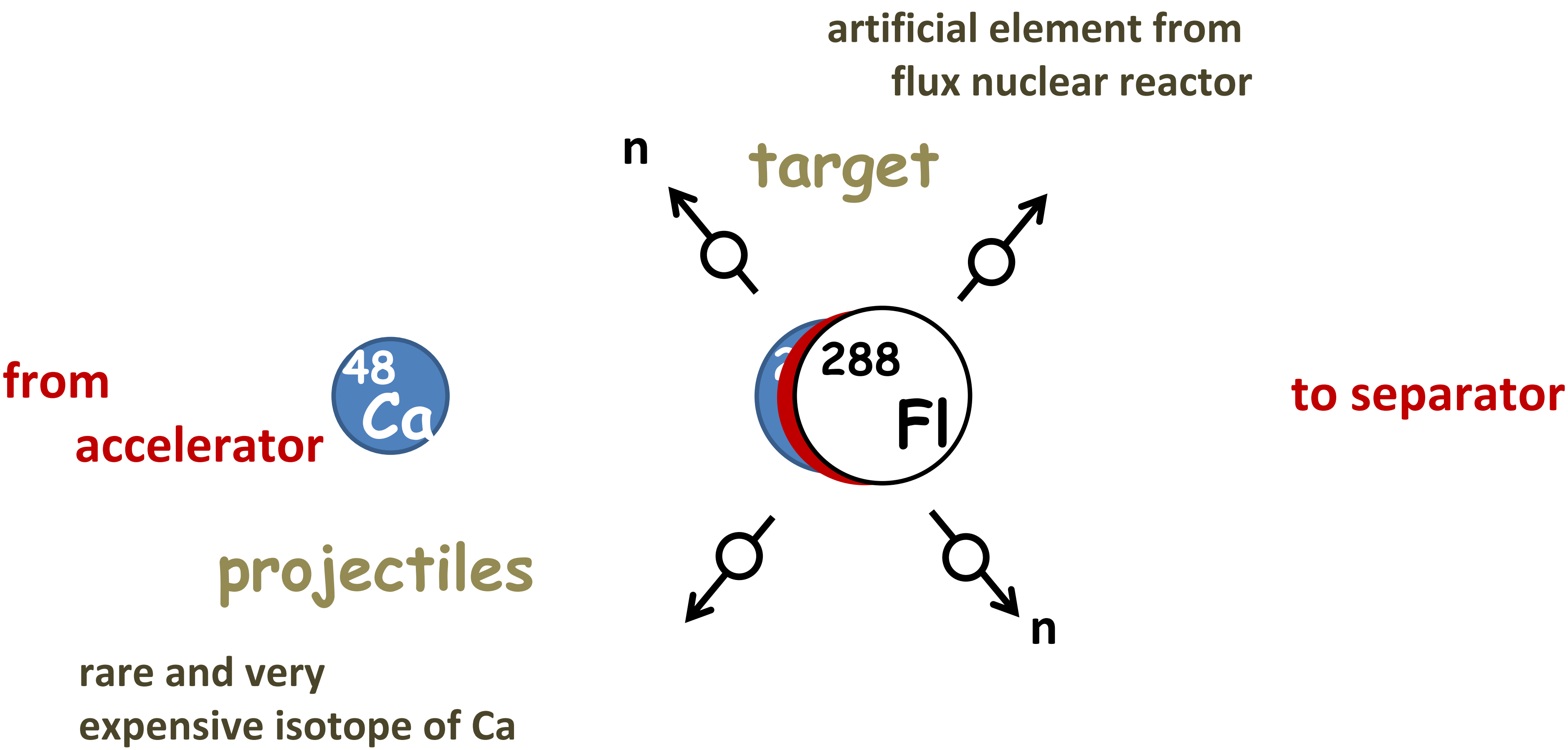
Yuri Oganessian. Discovery of SHN, Seminar of RIKEN, March 13, 2017, Tokyo, Japan

Reactions of Synthesis



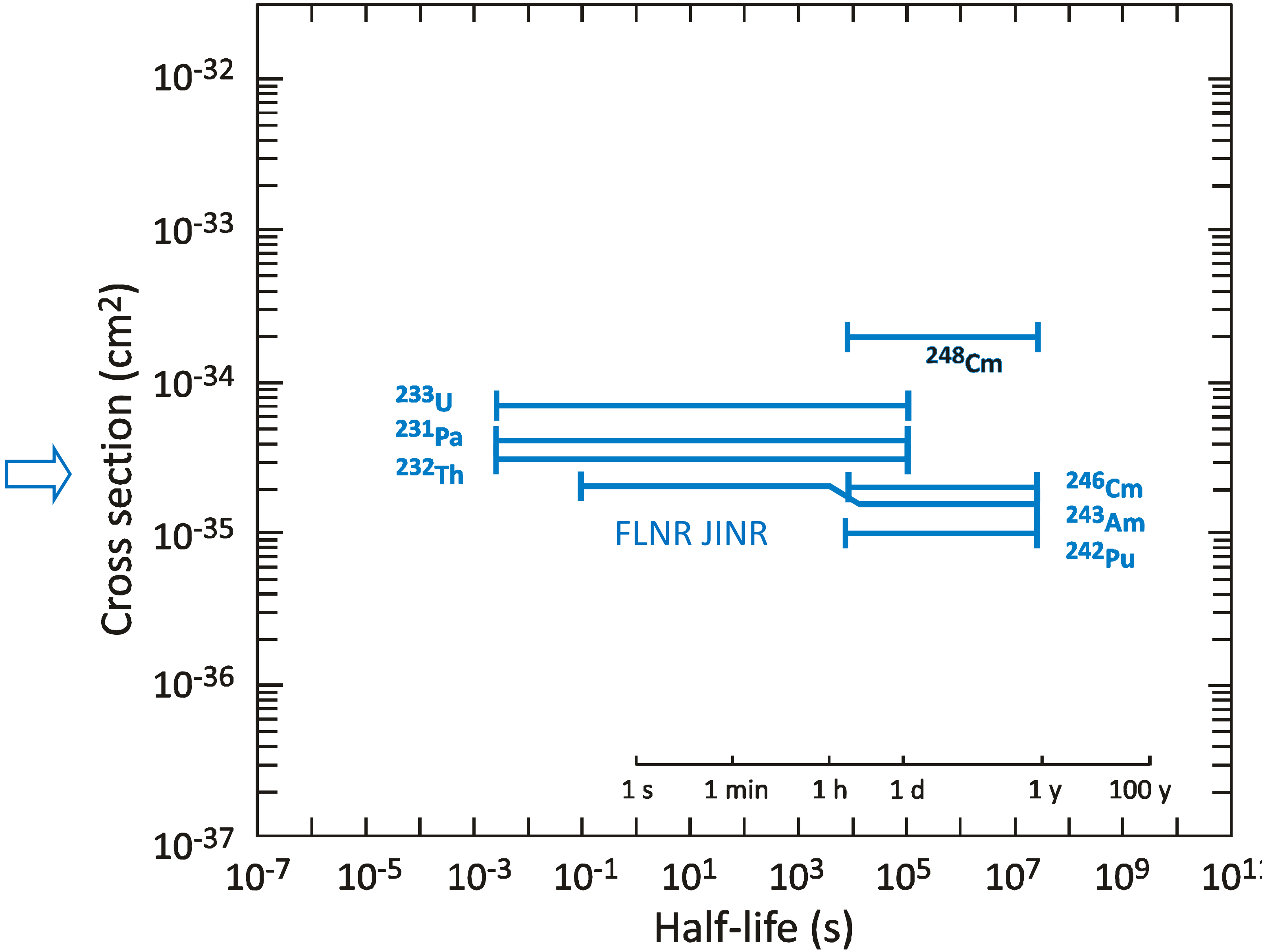
Historical background:

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


artificial element from
flux nuclear reactor
n
target
from
accelerator
48
Ca
288
Fl
to separator
projectiles
n
rare and very
expensive isotope of Ca

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

1977- 1979

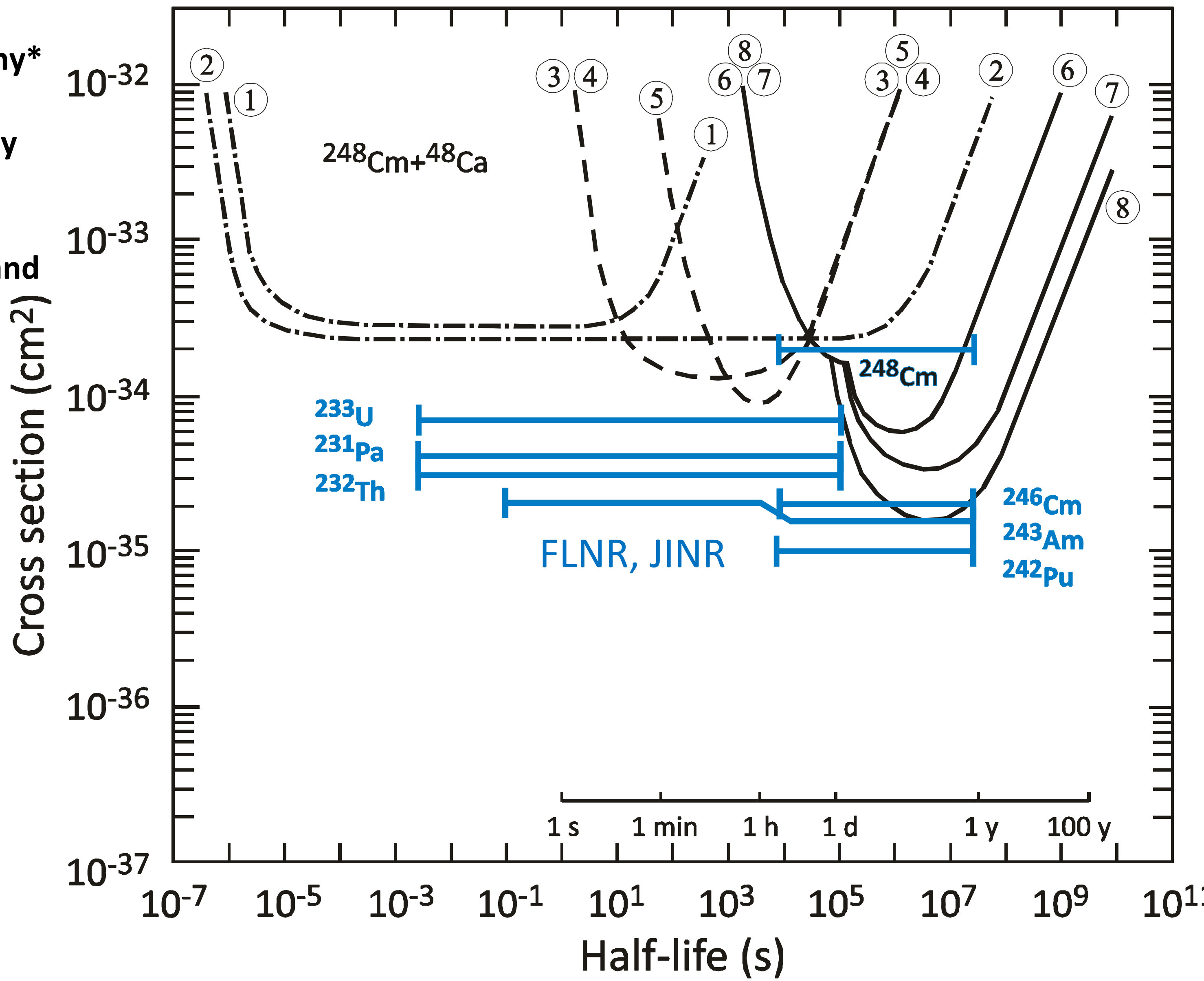


Experiments on the synthesis of Z=116 nuclei in the reaction $^{248}Cm+^{48}Ca$

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

1985 ⇨

1977- 1979 ⇨



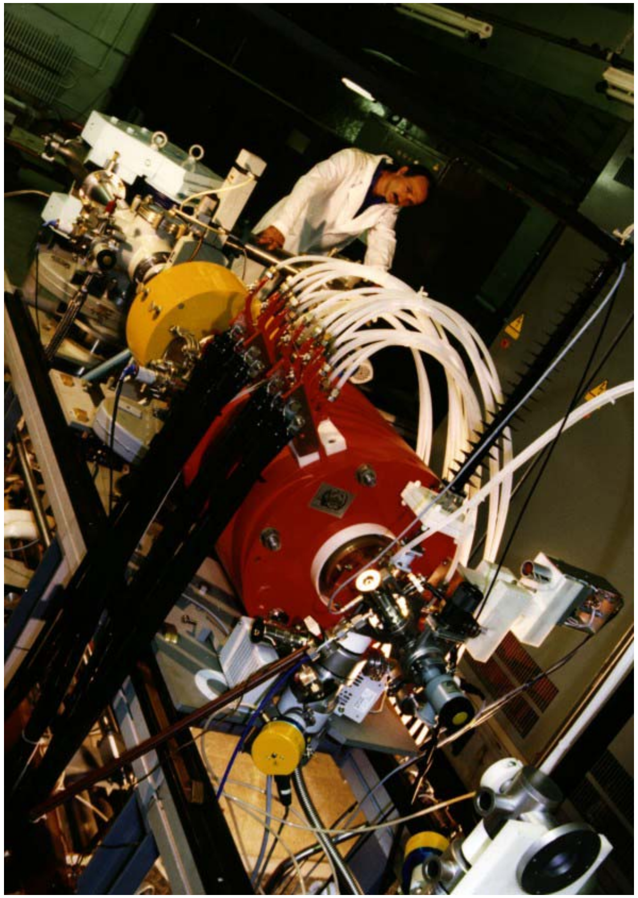
After this, an opinion arouse that the “Stability Island” may exist but this cannot be verified…

Here our opinions have diverged

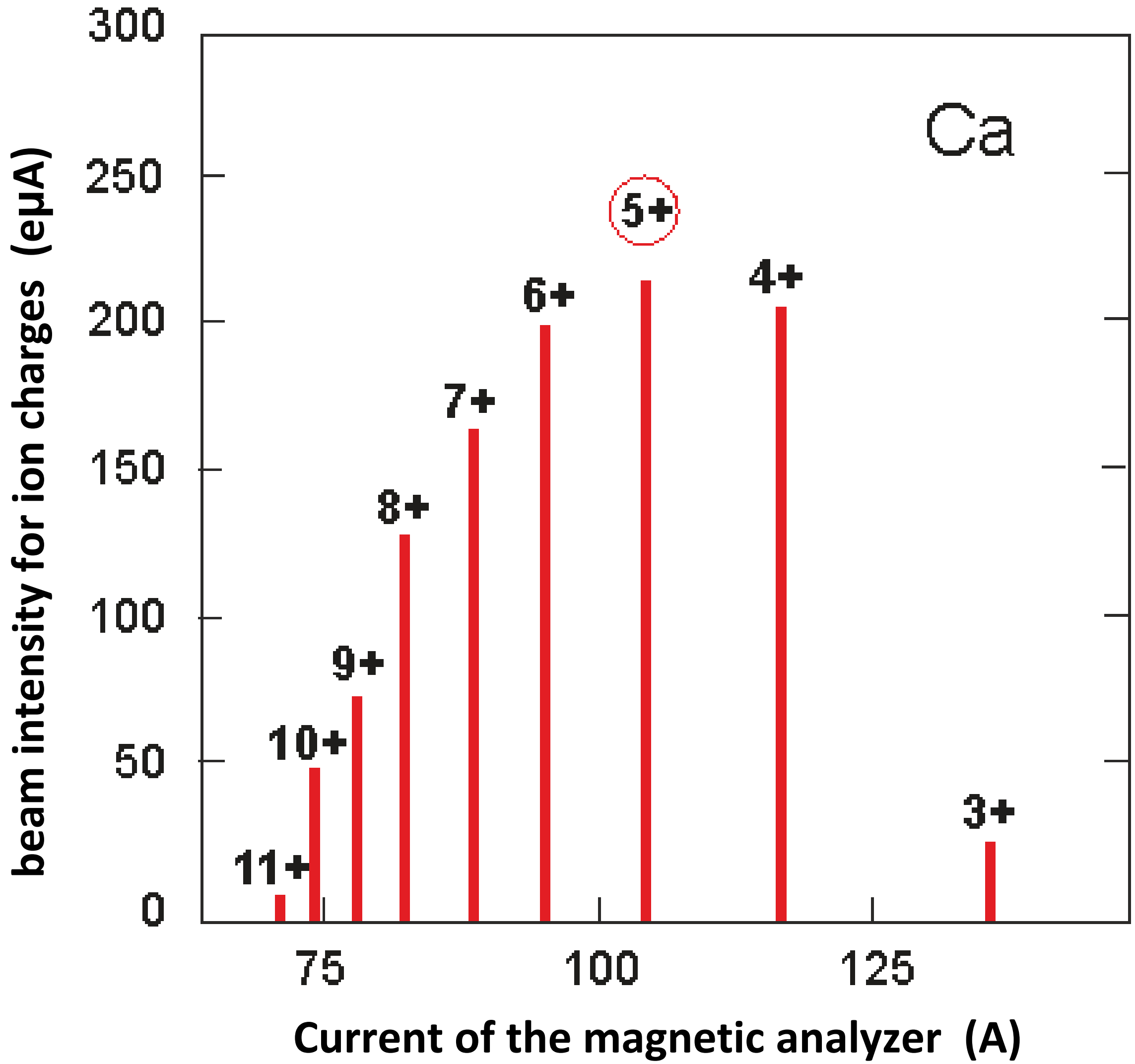
We did not share this view and, since the beginning of 1990, we started preparing:

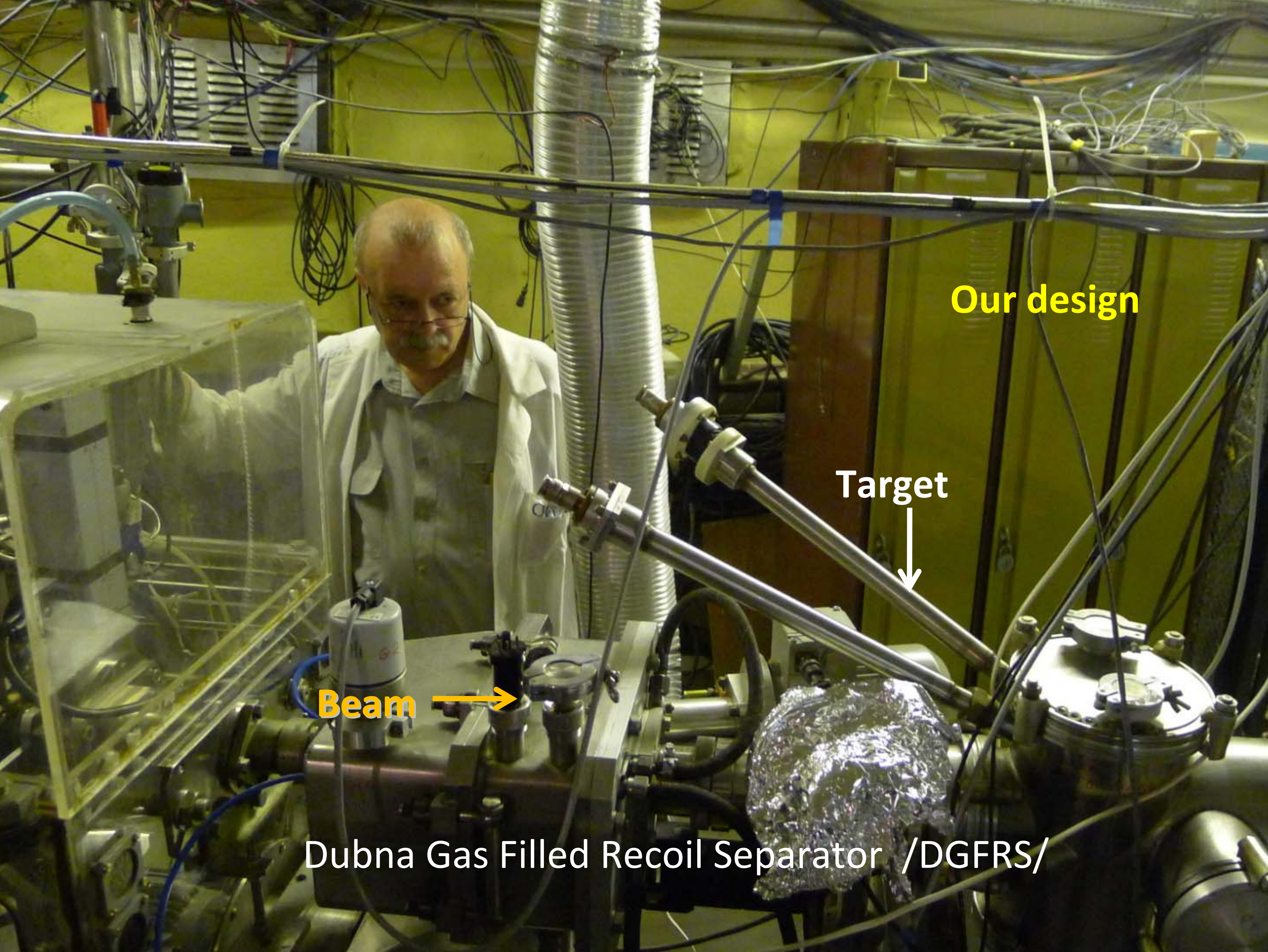
- development of a separator of superheavy nuclei in 1989
  (gas-filled separator of recoil nuclei)
- search for the target materials and manufacturing targets, 1990
  (collaboration with nuclear centers of Russia and USA)
- production of intense beam of Ca-48 in 1996
  (new type of ion source ECR-4M)
- getting ready to long-term experiments, 1990-97.

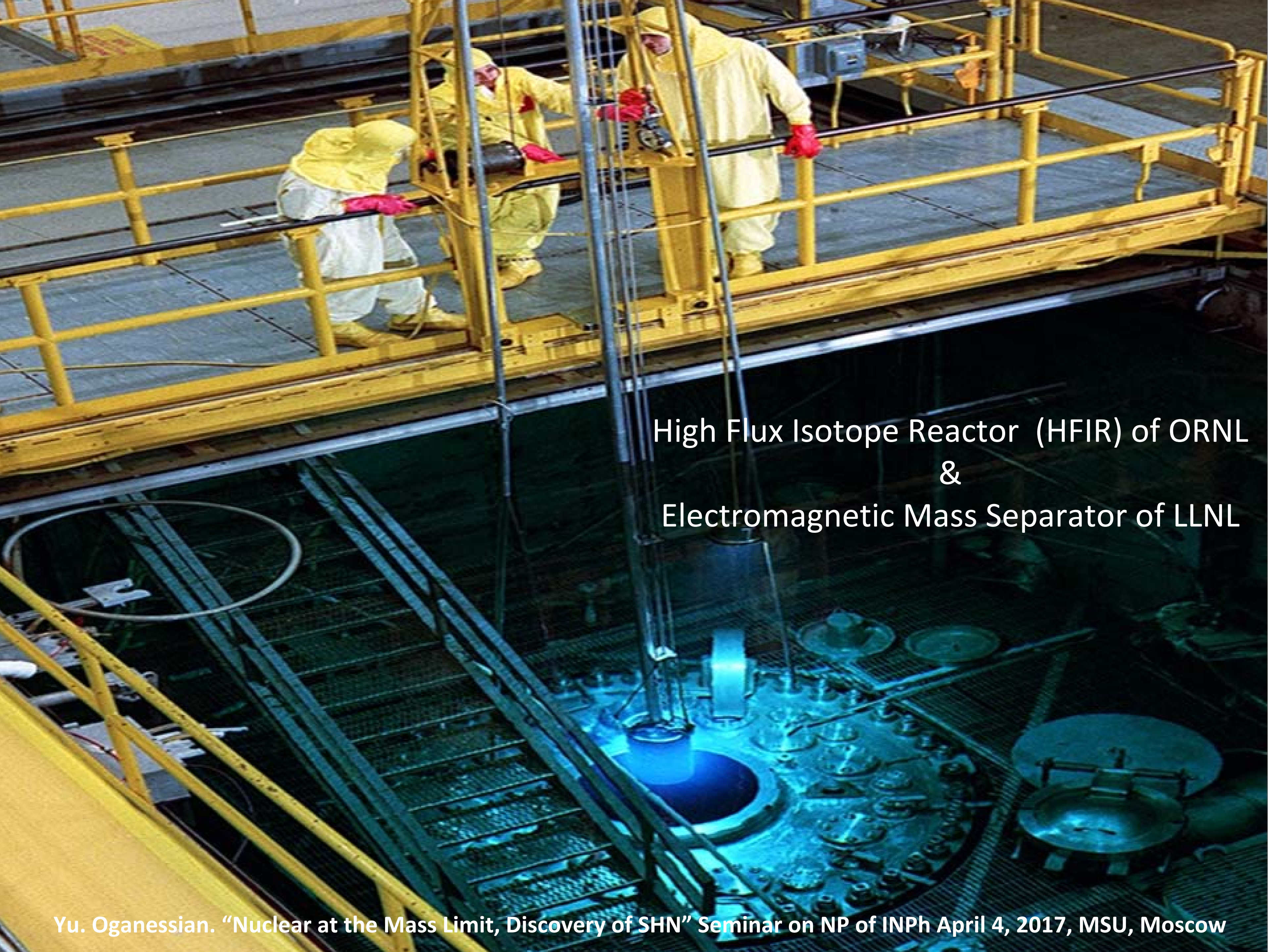
Ion charge distribution of Ca-48 extracted from 14 GHz ECR-ion source



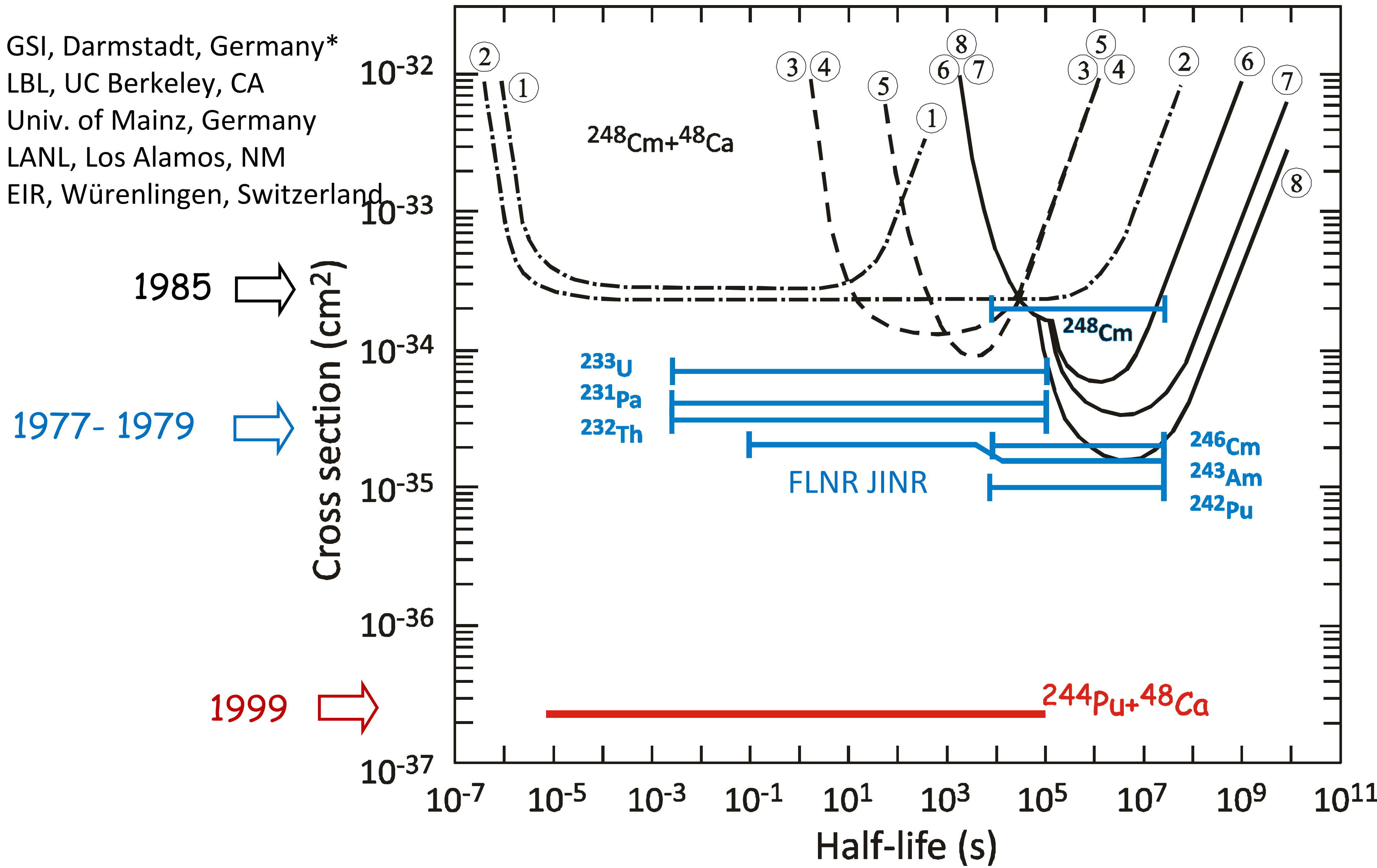
Our modification of GANIL source



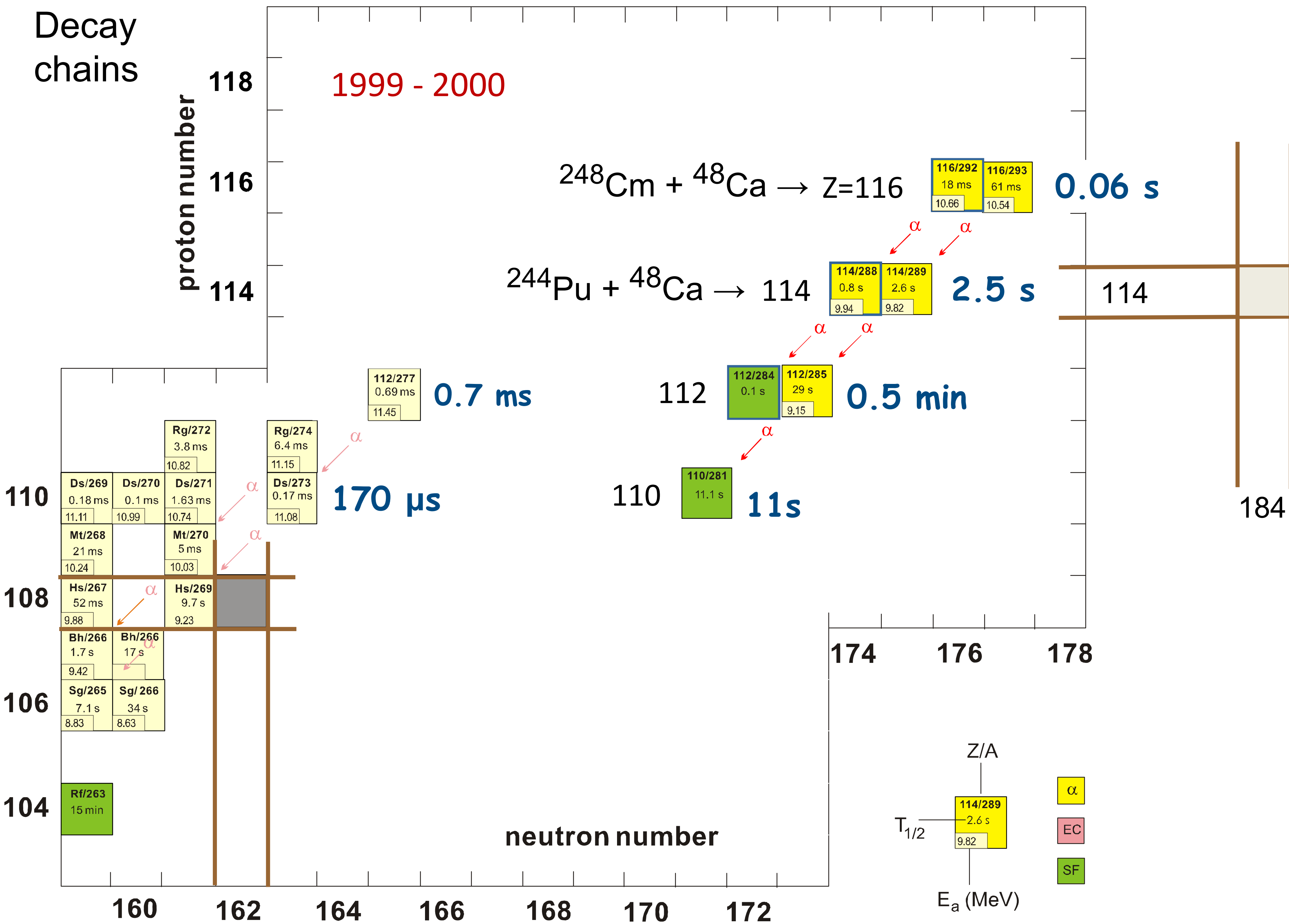

Our design
Target
Beam
Dubna Gas Filled Recoil Separator /DGFRS/


High Flux Isotope Reactor (HFIR) of ORNL
&
Electromagnetic Mass Separator of LLNL

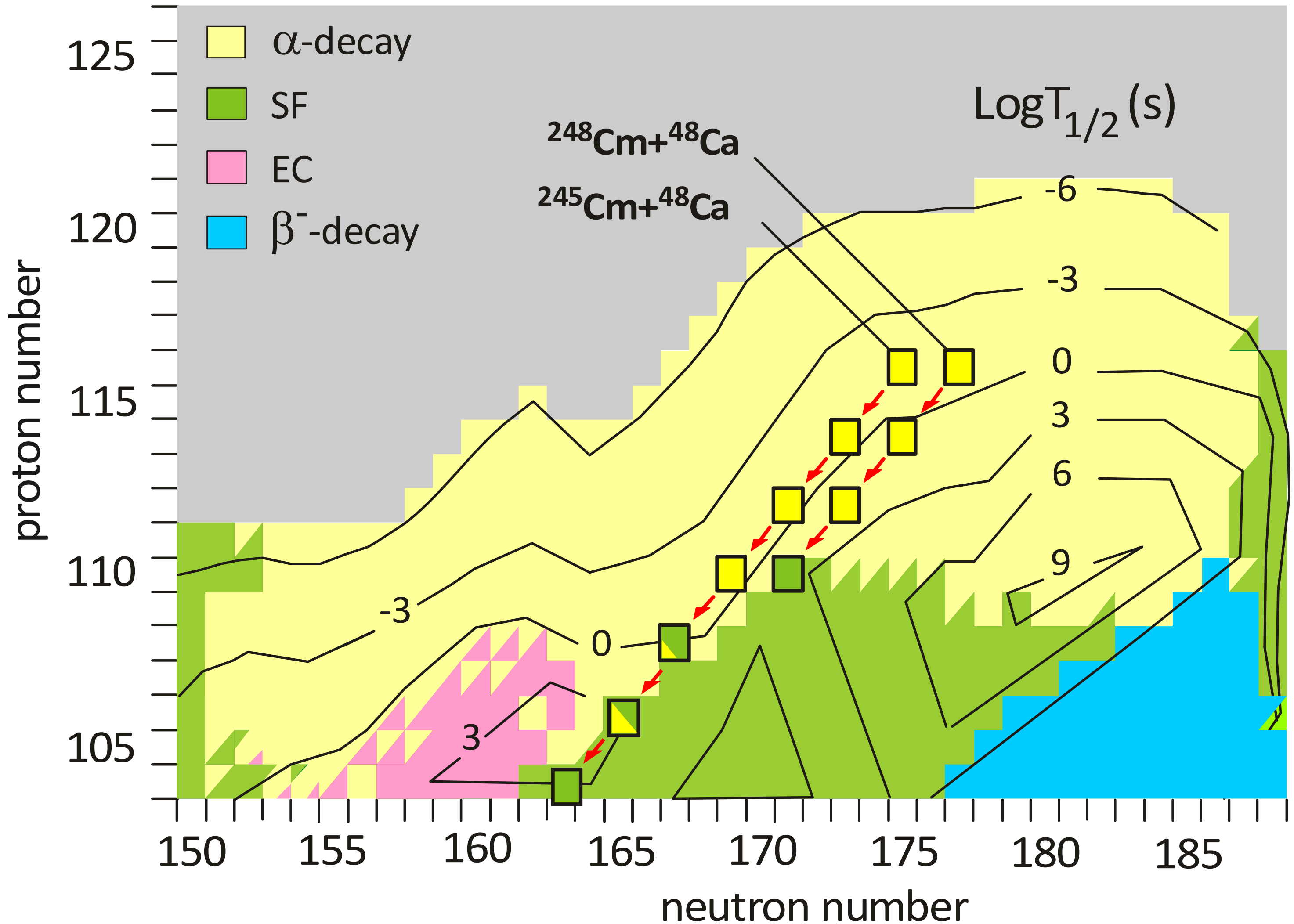
Experiments on the synthesis of SHE in ^{48}Ca induced reaction



Decay chains



Decay chains of the isotopes of Element 116: ^{291}Lv and ^{293}Lv

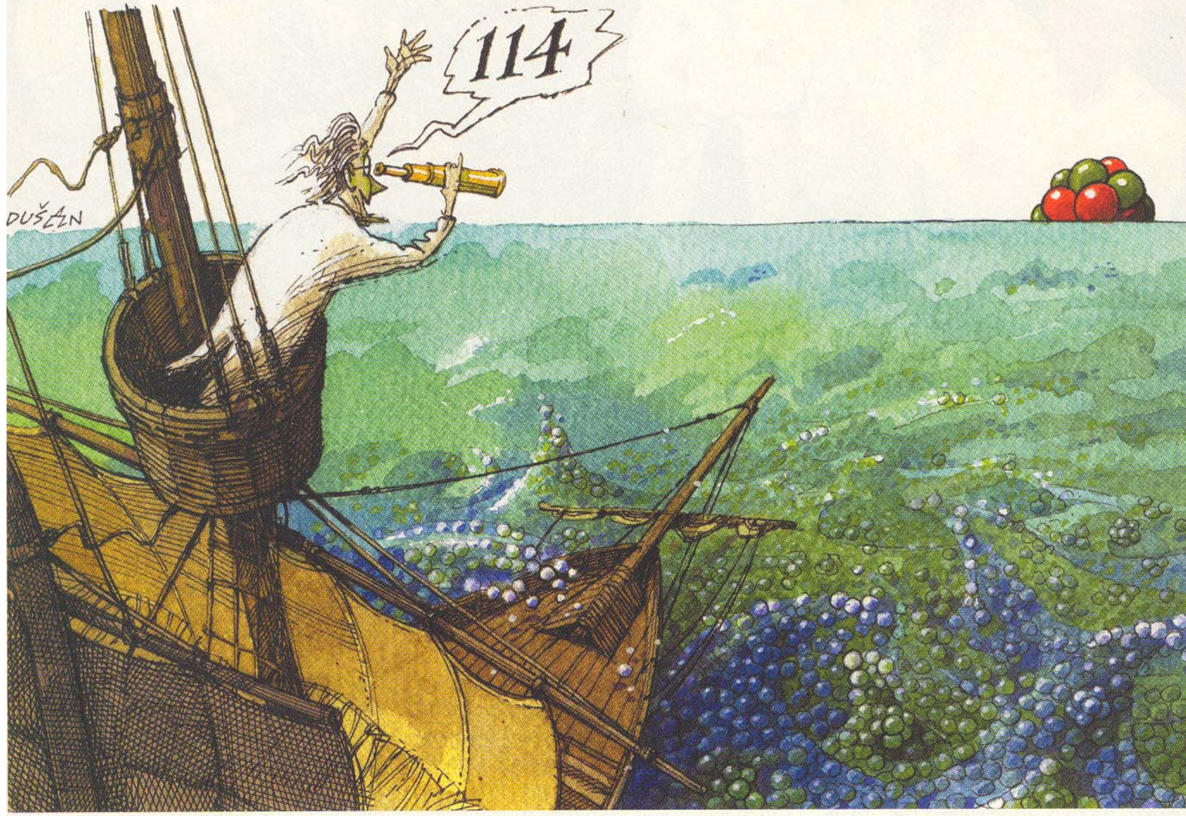


Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

an Article from **SCIENTIFIC AMERICAN**

JANUARY 2000 VOL. 282 NO. 1

Voyage to SUPERHEAVY Island



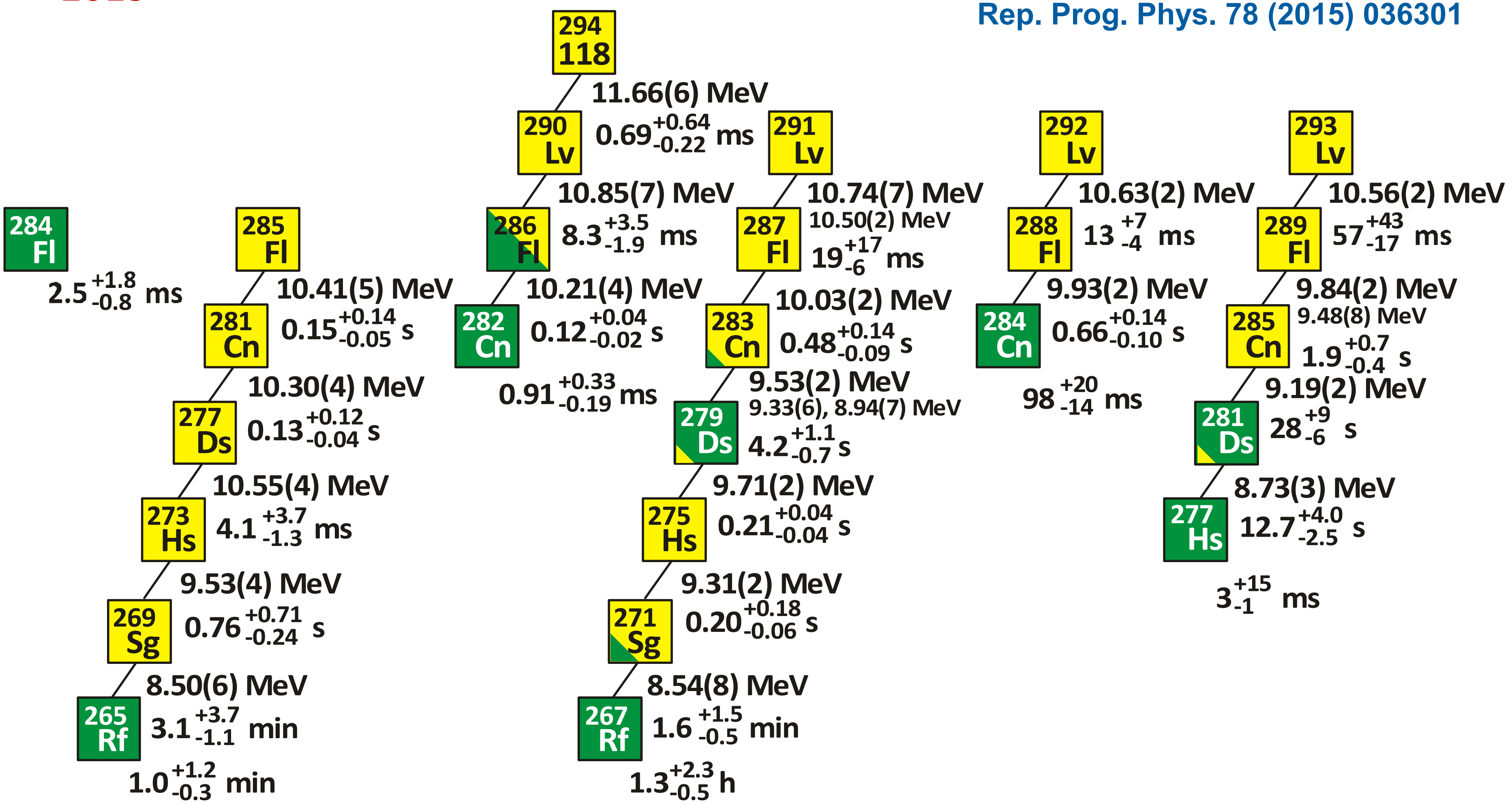
The synthesis of element 114 confirmed decades-old theoretical predictions of a little patch of nuclear stability in a sea of short-lived superheavy nuclei

Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

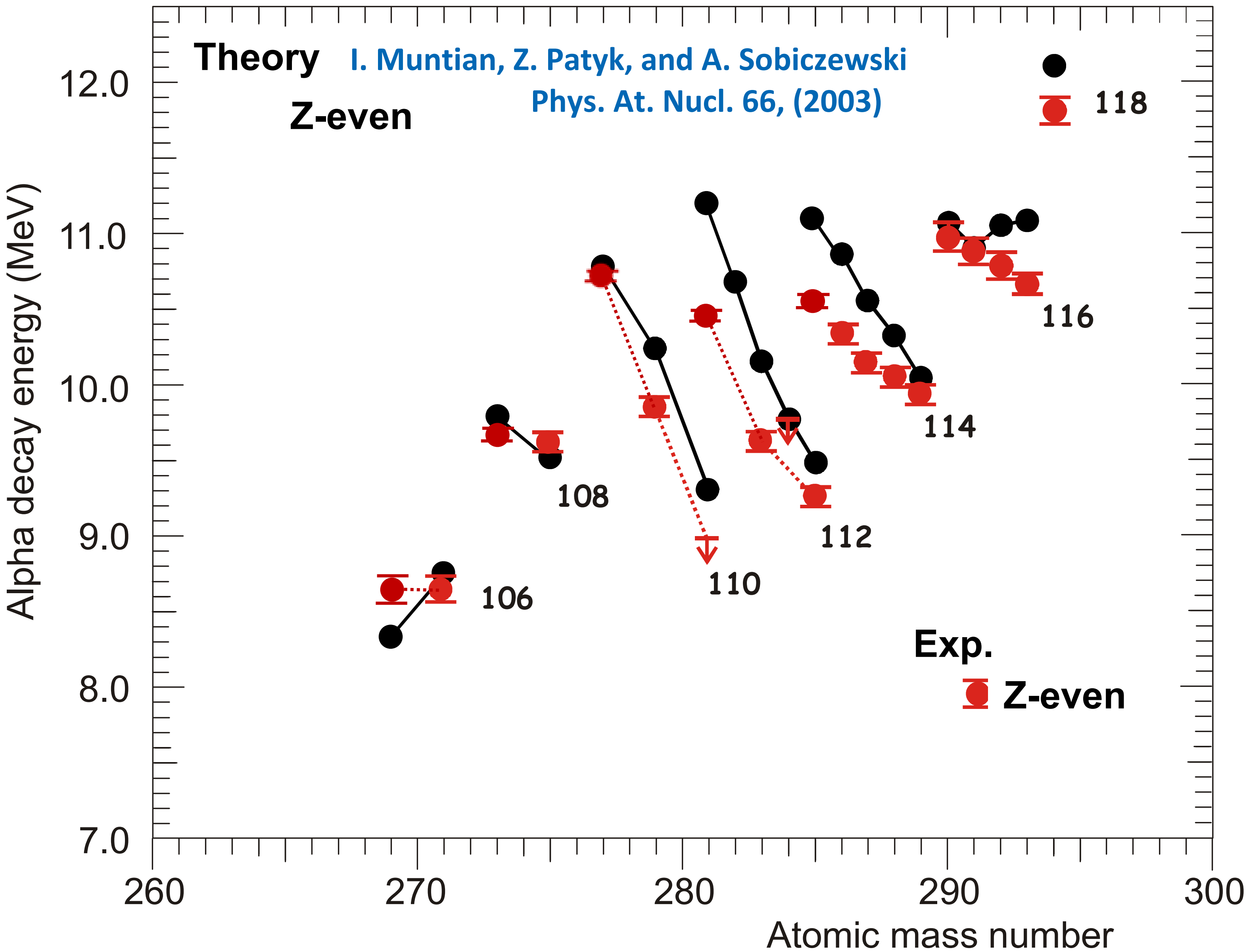
Summary decay properties of the isotopes of elements 112, 114, 116 and 118 observed in **^{238}U, ^{240,242,244}Pu, ^{245,248}Cm** and **^{249}Cf** + **^{48}Ca** reactions

2015

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

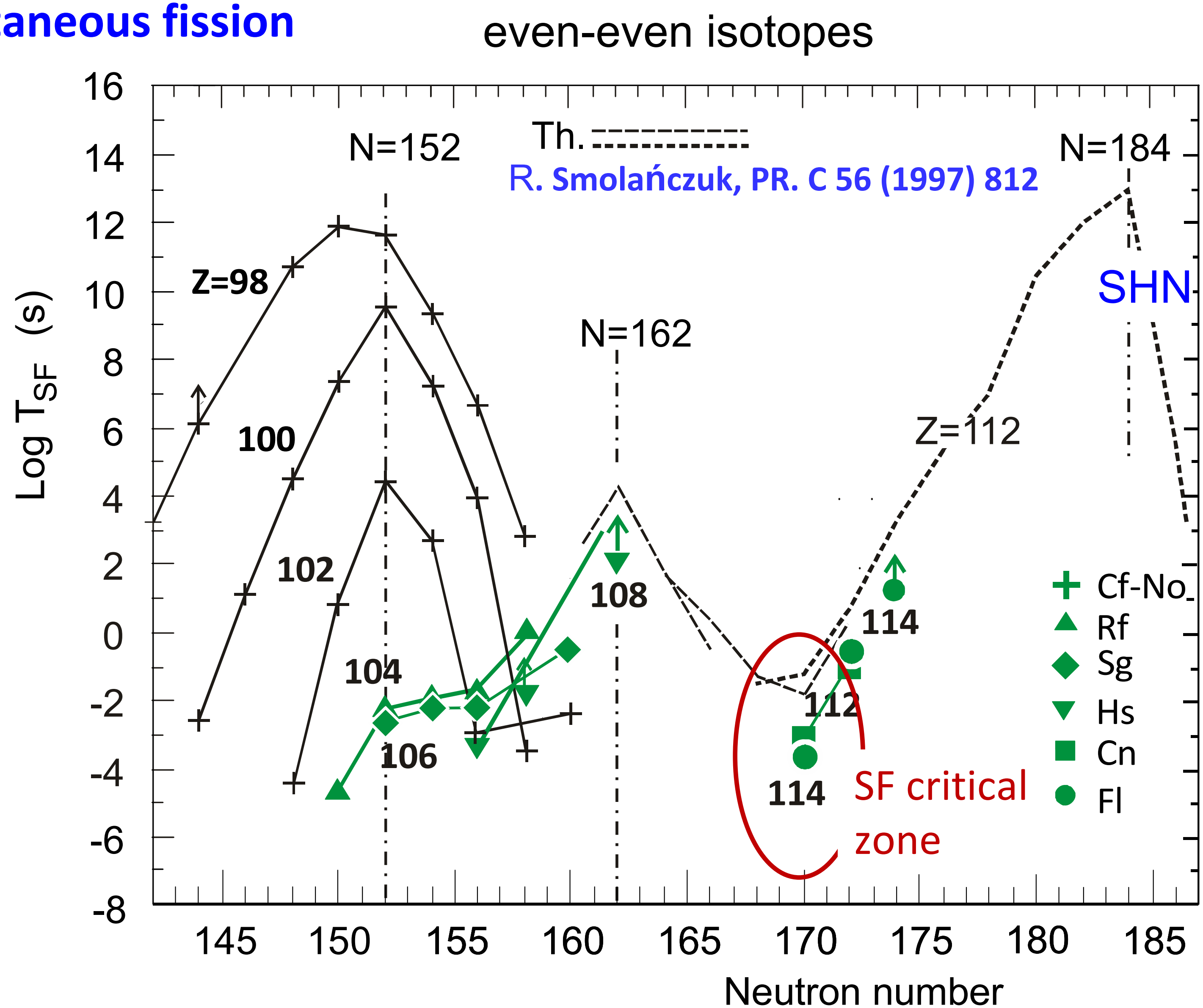


Alpha - decay



Theory
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



Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

Cross sections

hot fusion

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

E_x = 40 - 45 MeV

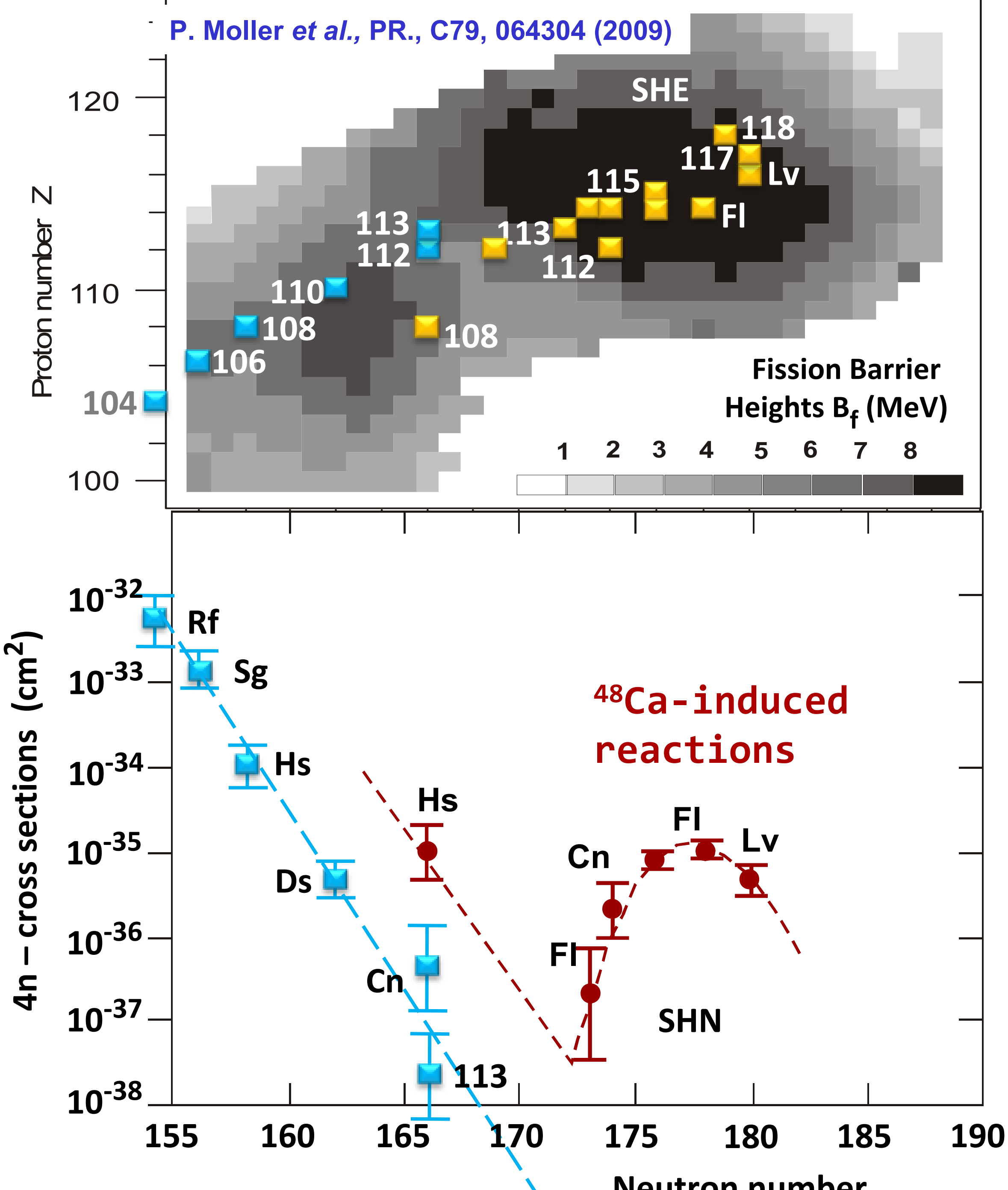
x = 4 –5

cold fusion

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

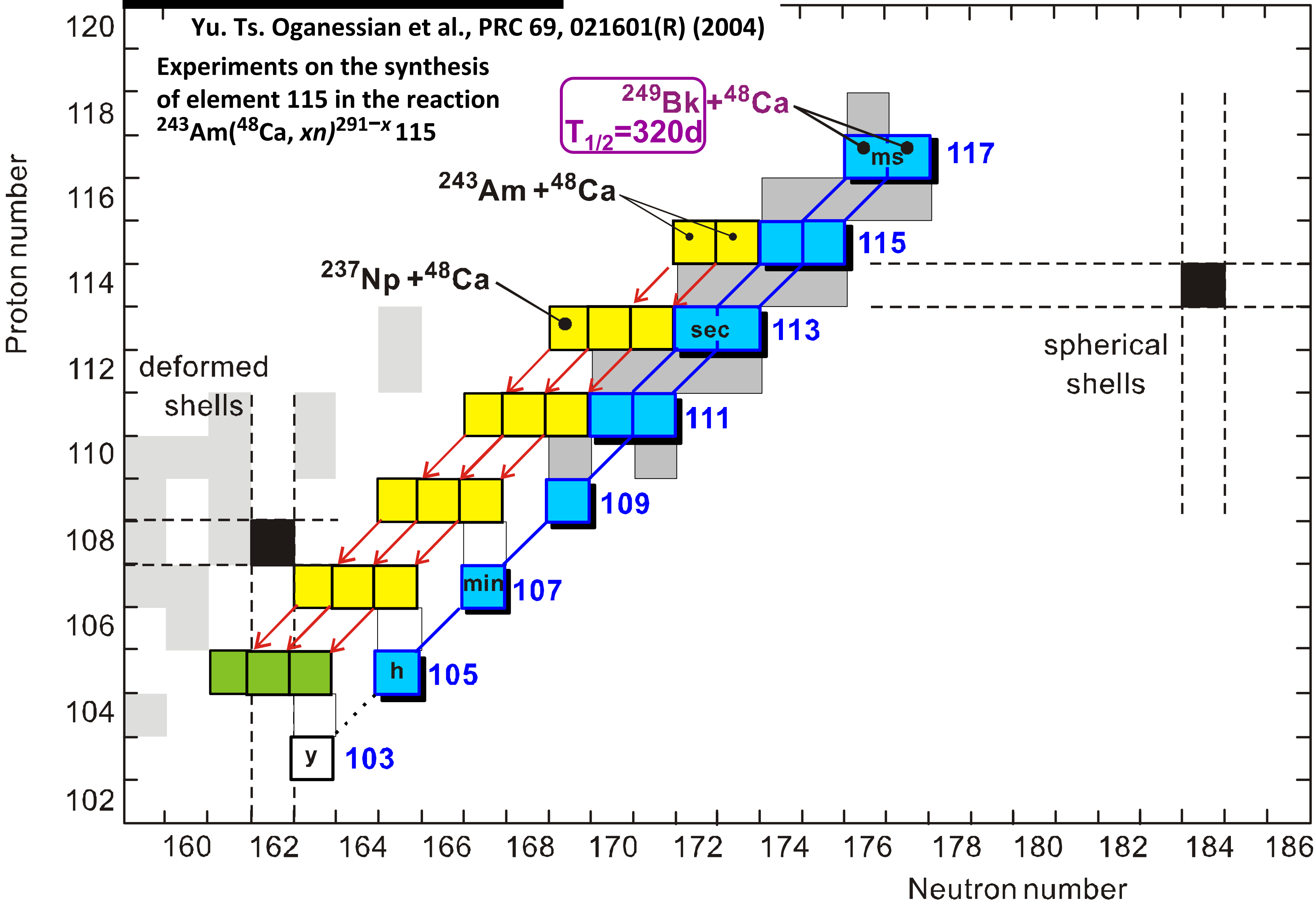
E_x = 12 - 15 MeV

x = 1



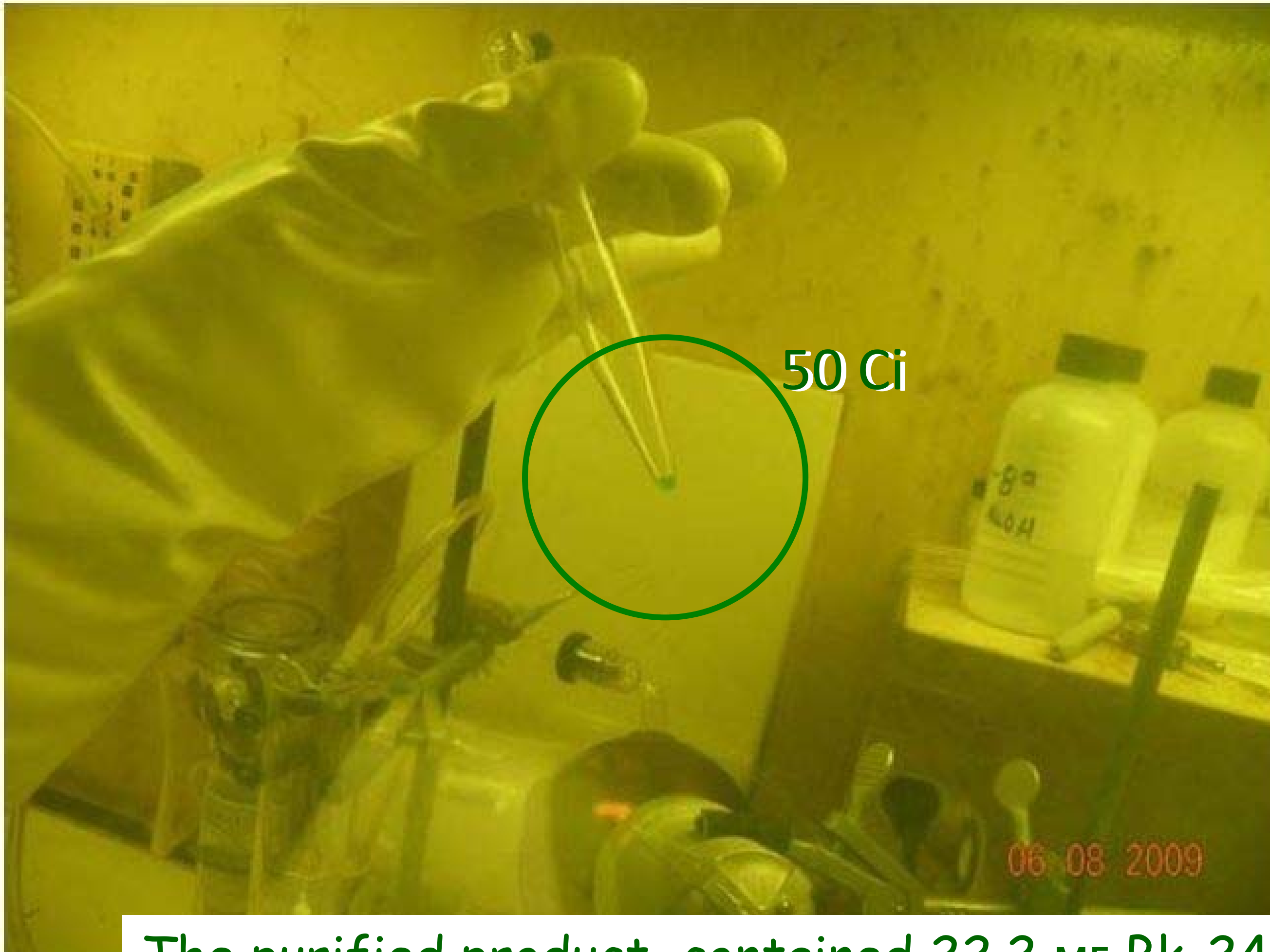
Odd-Z Superheavy Nuclei

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



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
^{249}Bk+^{48}Ca
$T_{1/2}$=320d
^{243}Am+^{48}Ca
^{237}Np+^{48}Ca
ms
sec
min
h
y
117
115
113
111
109
107
105
103
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

Berkelium -249 at hot cell

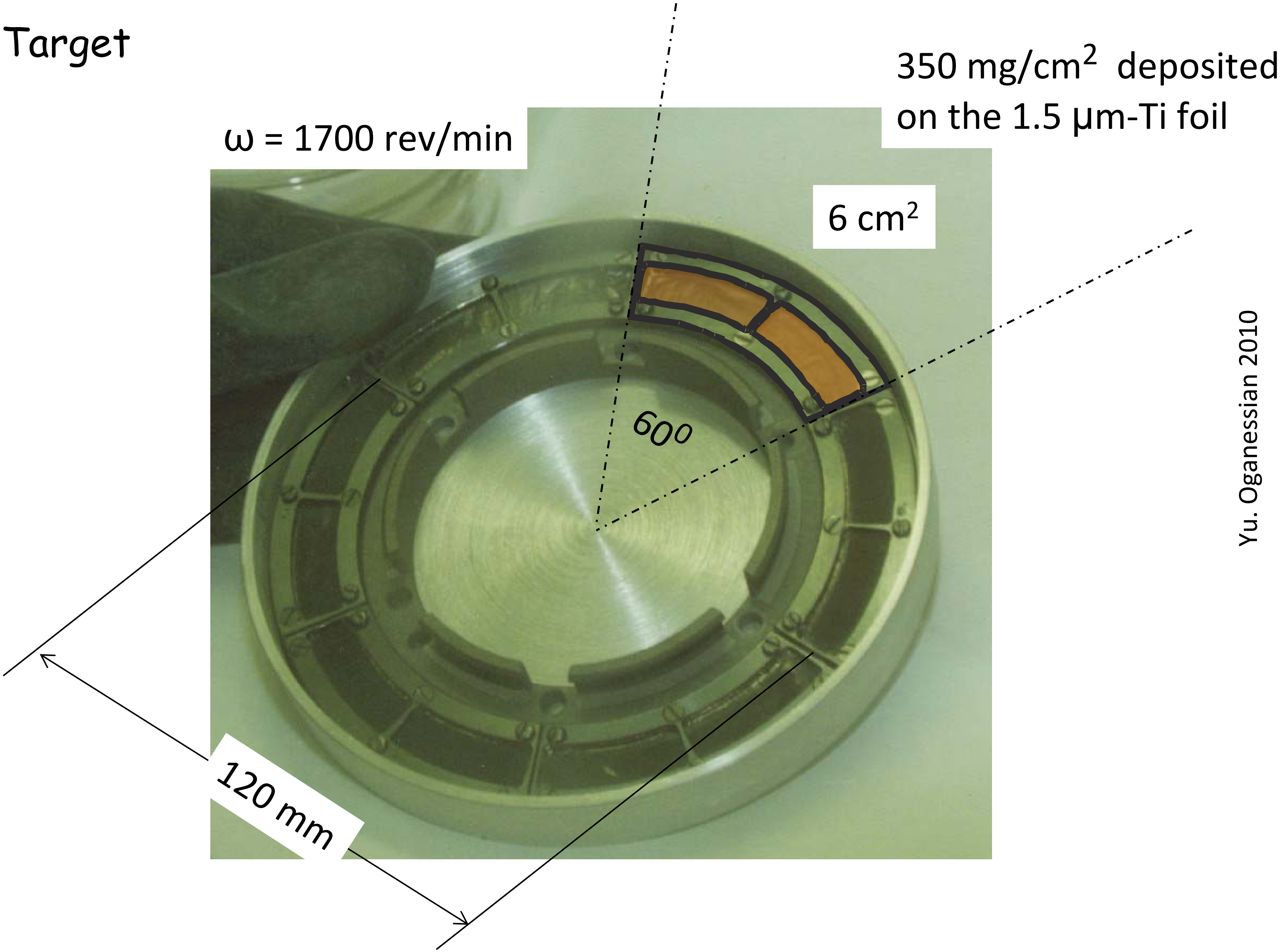


The purified product contained 22.2 мг Bk-249

$Bk(NO_3)_3$Product

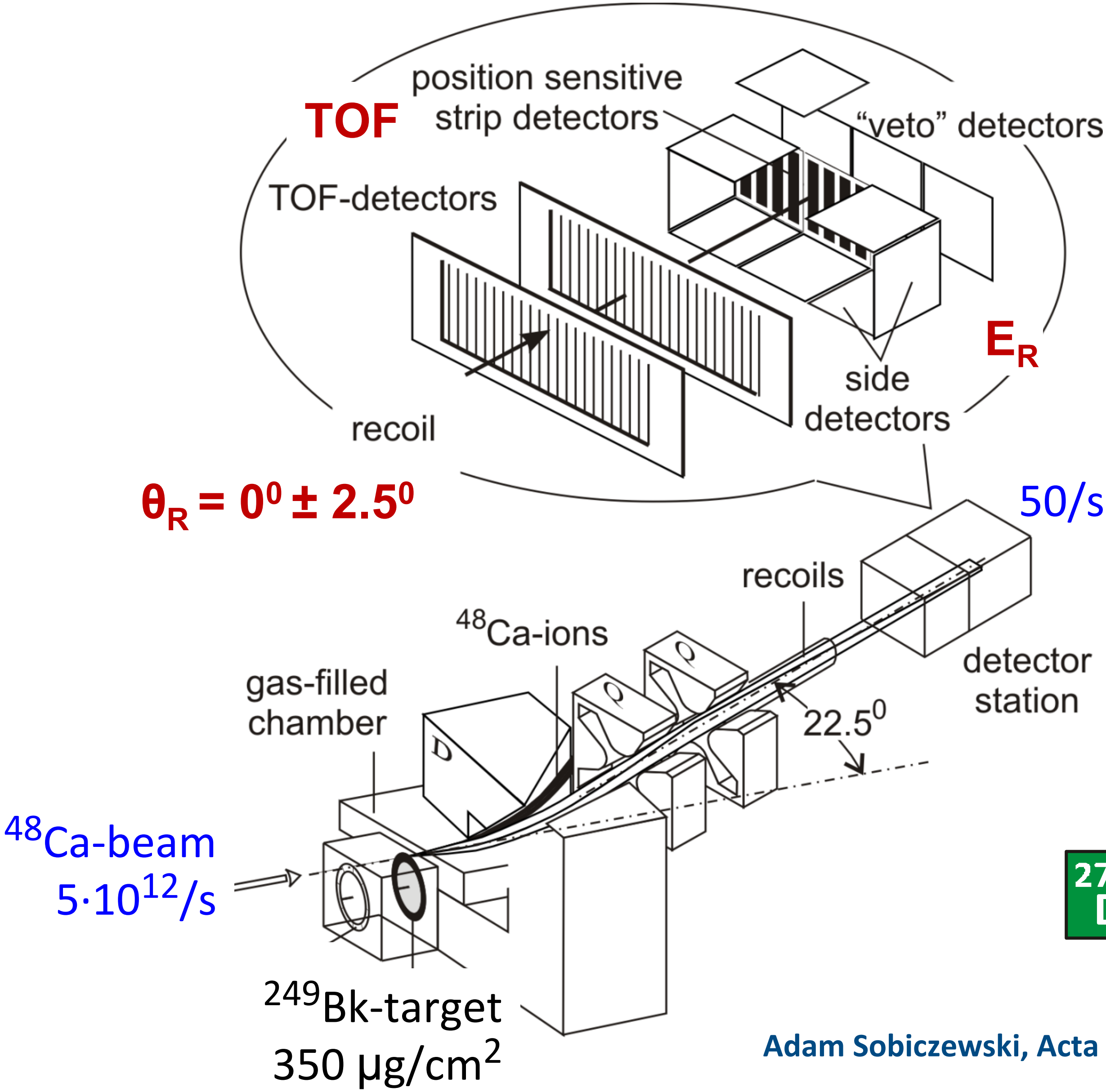
Yu. Oganessian 2010

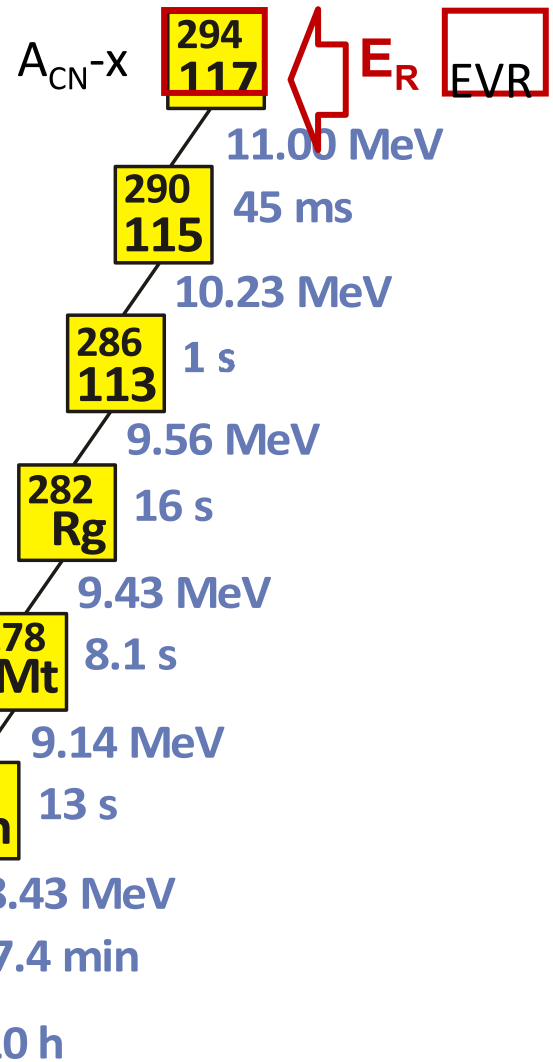
Target



Yu. Oganessian 2010

Dubna Gas-Filled Recoil Separator DGFRS

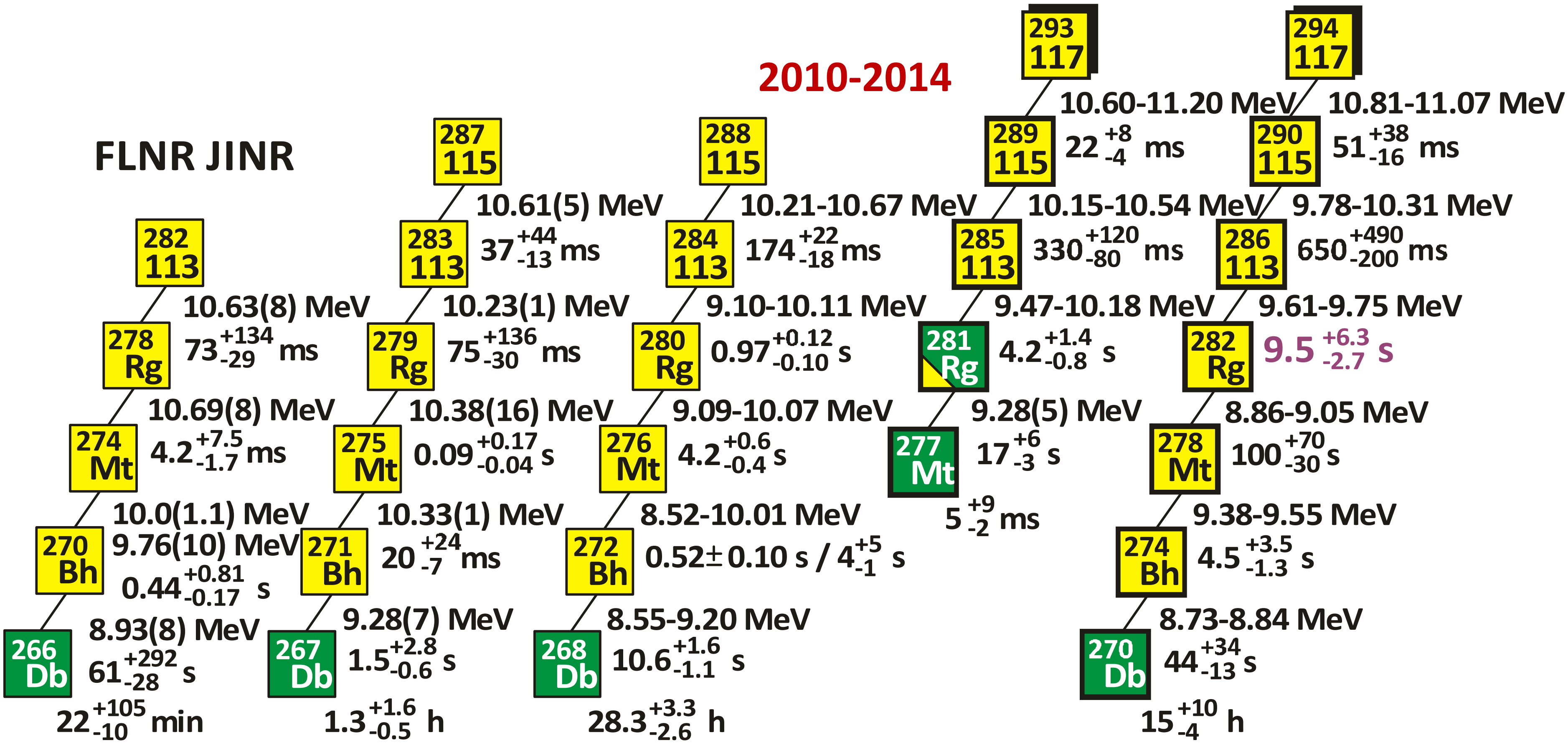




Adam Sobiczewski, Acta Phys. Pol. B 41, 157 (2010).


Beam dose 1.5*10^19
~50 days
3*10^17 per day
1 pμA
Beam current (emA)
0
10
20
30
27
1
10
20
30
40
50
Time (days)
Time (days)
Heavy Ion Accelerator, FLNR
Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

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



Yu. Oganessian. “Nuclear at the Mass Limit, Discovery of SHN” Seminar on NP of INPh April 4, 2017, MSU, Moscow

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)
$^{288, 289}114$	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)

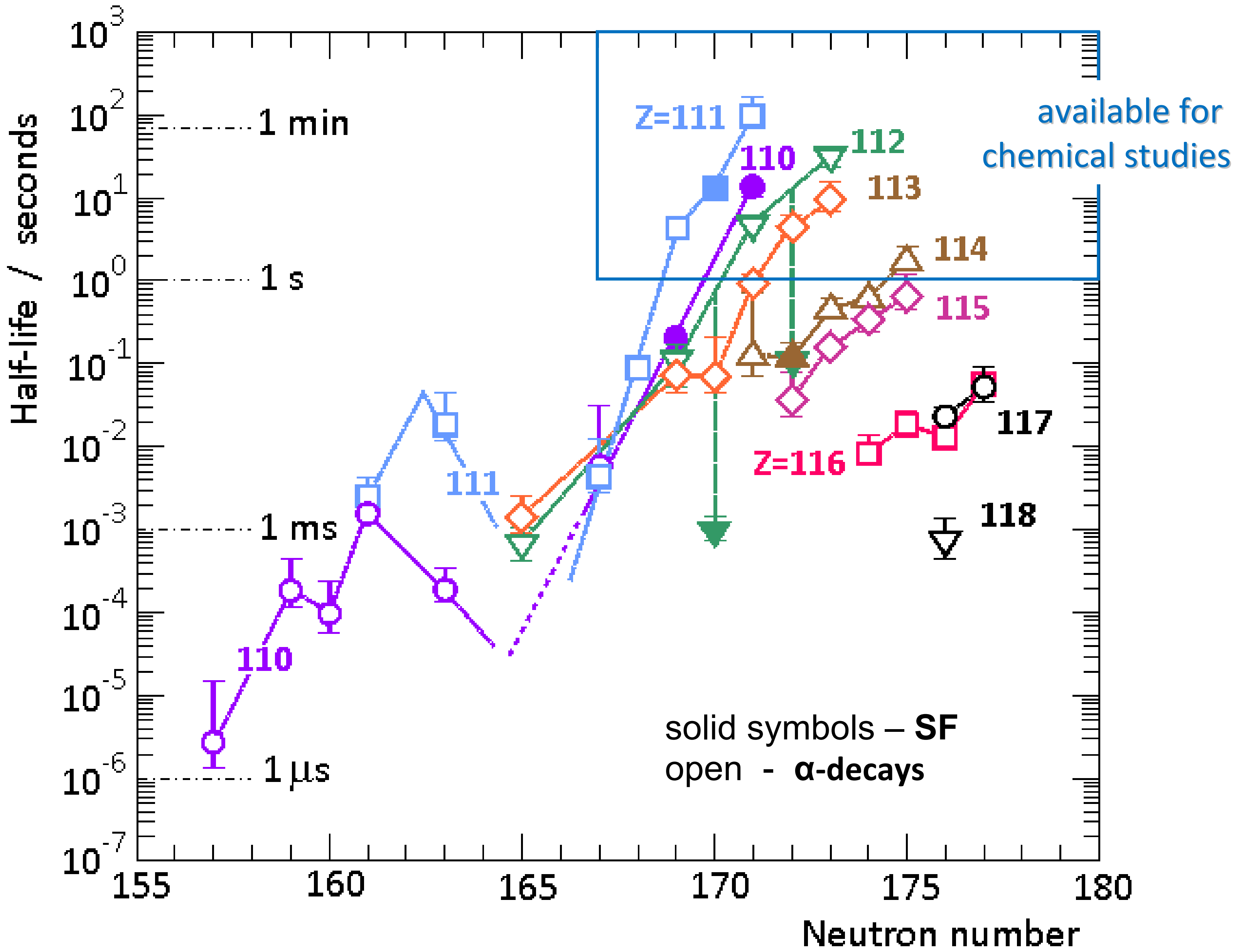
With Z >40% larger than that of Bi, the heaviest stable element we see an impressive extension in nuclear survivability.

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

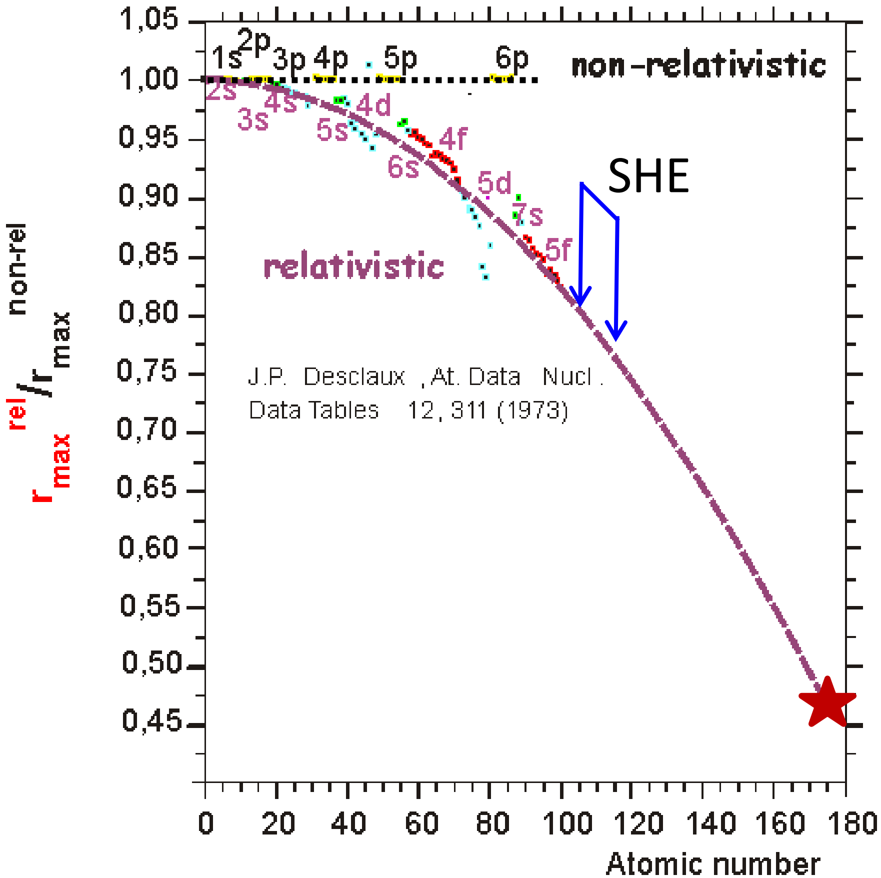


Yu. Oganessian. "Nuclear at the Mass Limit, Discovery of SHN" Seminar on NP of INPh April 4, 2017, MSU, Moscow

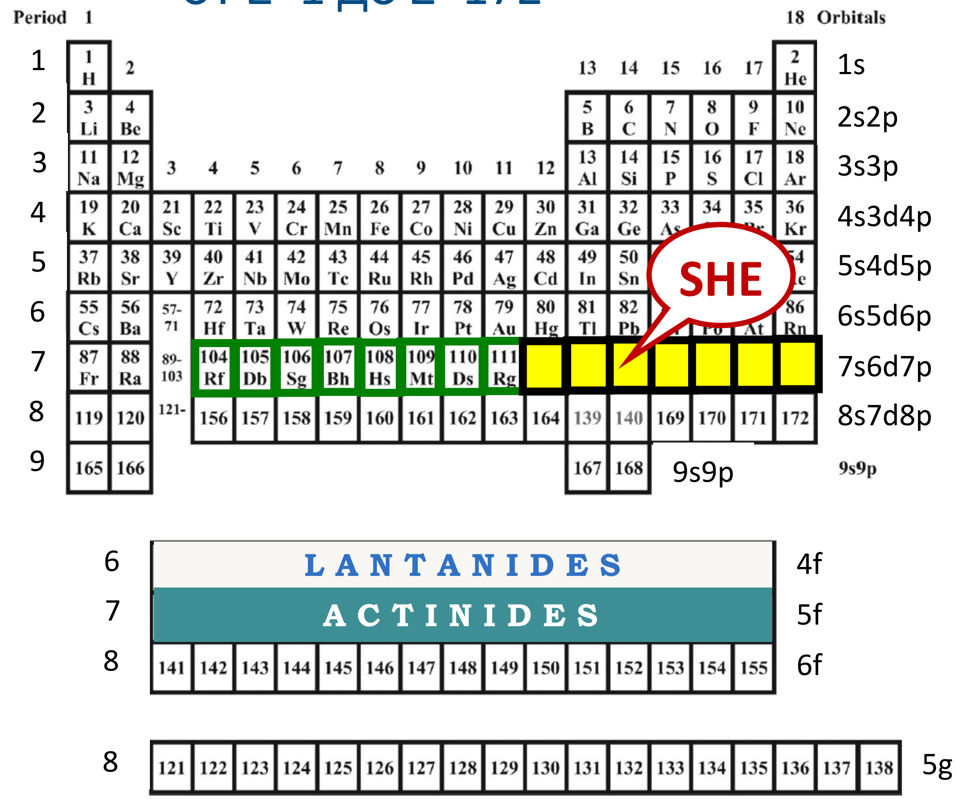
Super Heavy Atoms

Chemistry of the SHE

Table of Elements
от Z=1 до Z=172



Relativistic Contraction



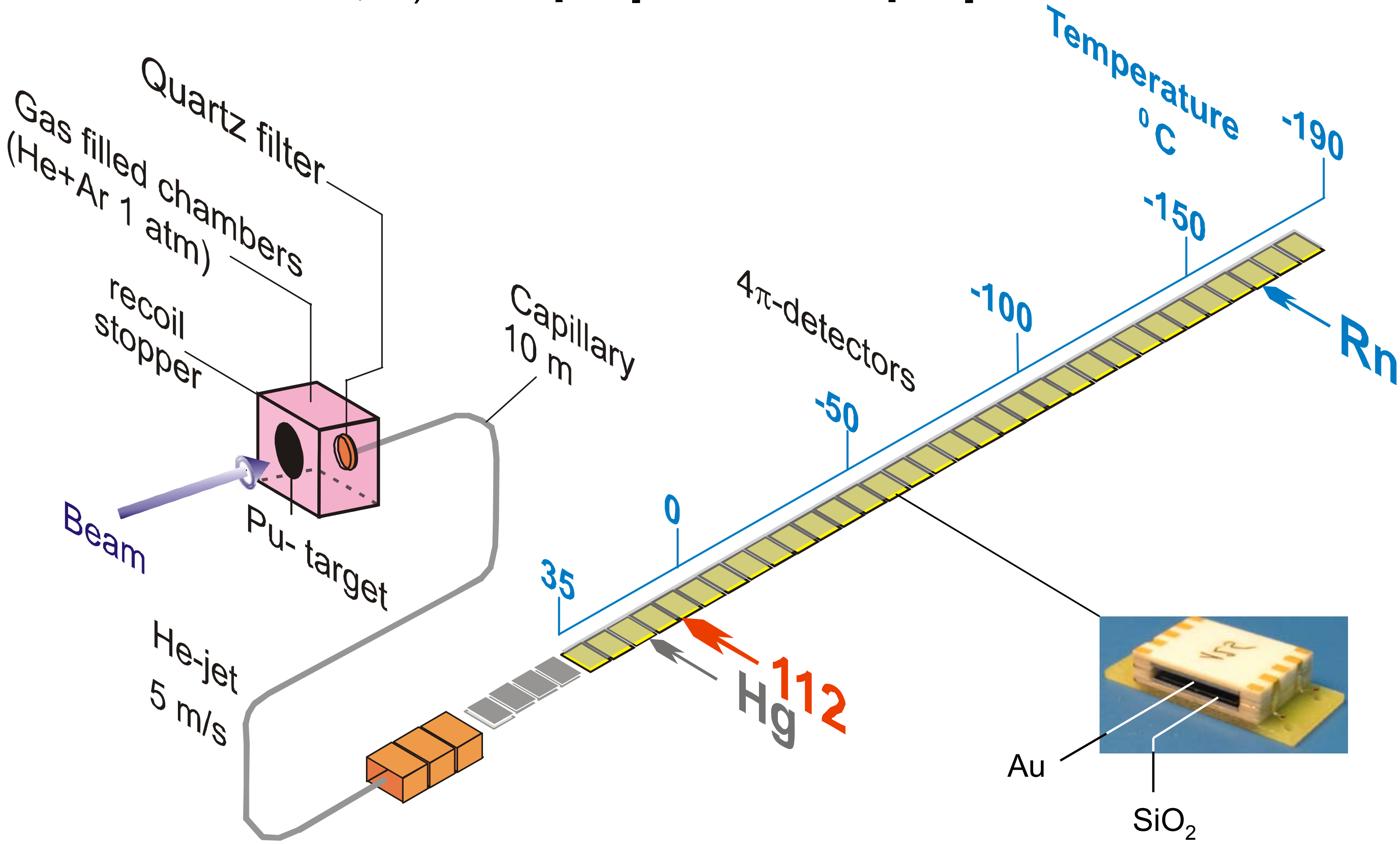
Calculated by P. Dirac and V. Fock
in non-relativistic approximation

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

Compounds: **Hg(Au)** and **112(Au)**

Reaction:

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



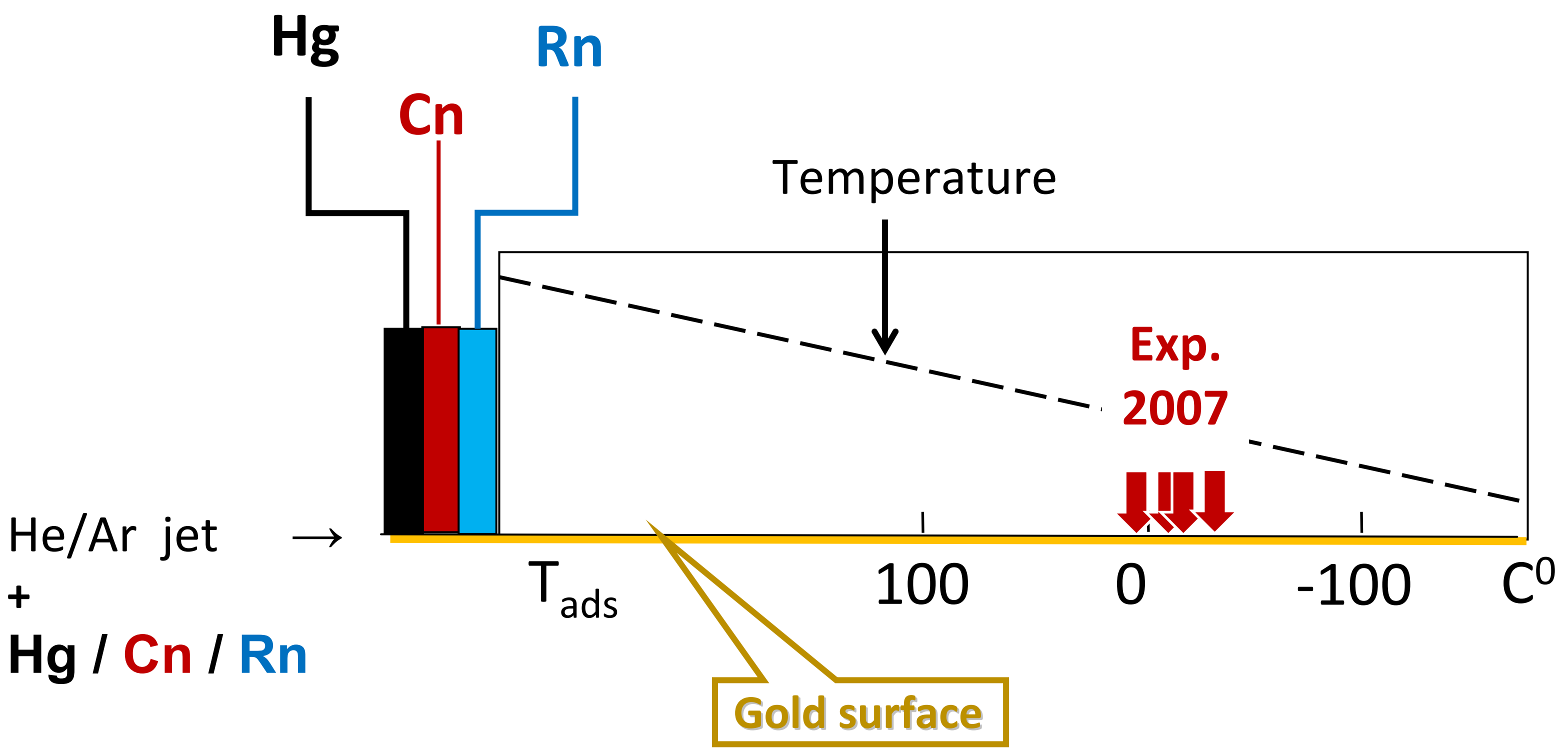
Relativistic Effect in Chemistry of the Element 112

FLNR, JINR 2007

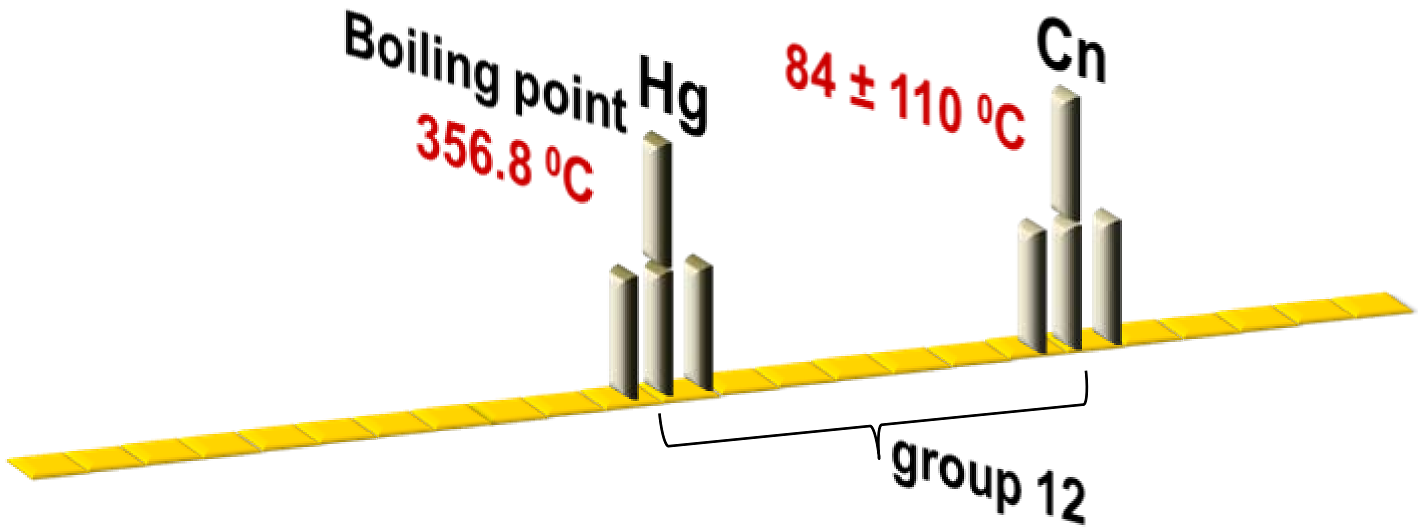
Adsorption of Hg and Cn (Z=112) on the Gold Surface

V. Pershina, 2006 (theory)

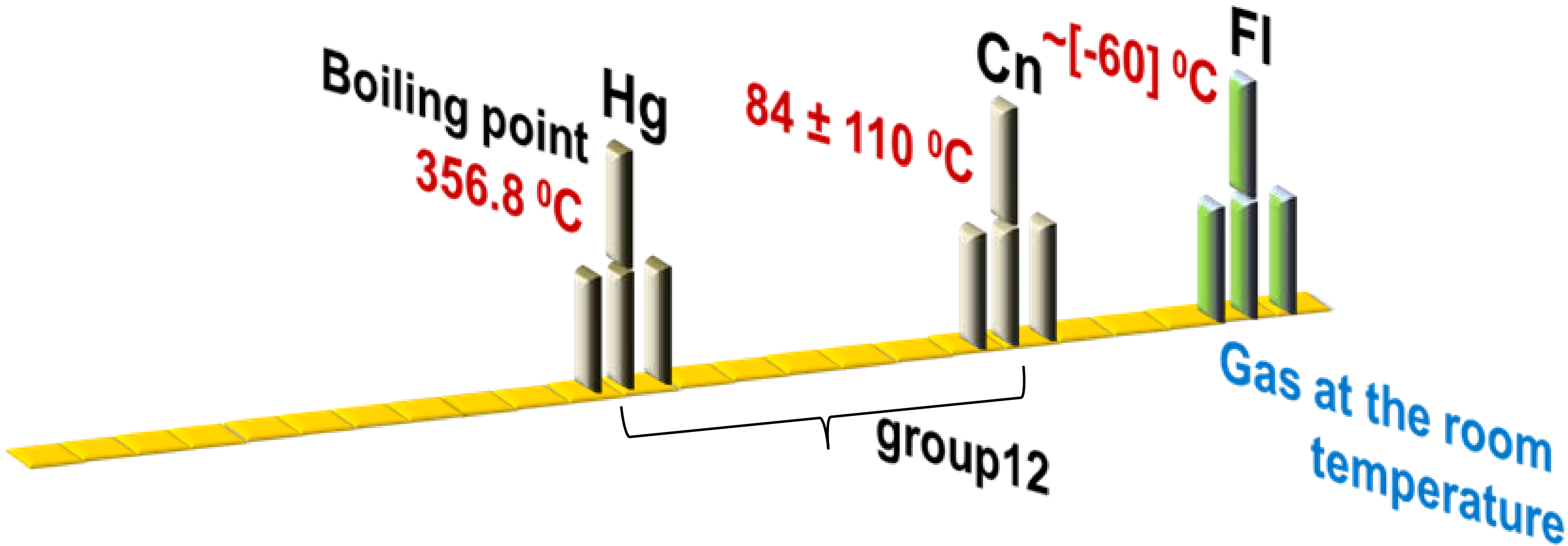
$^{242}Pu(^{48}Ca,3n)\ ^{287}Fl \rightarrow\ ^{283}Cn$



Thermo chromatography of the SHE and its light homologies on the gold surface

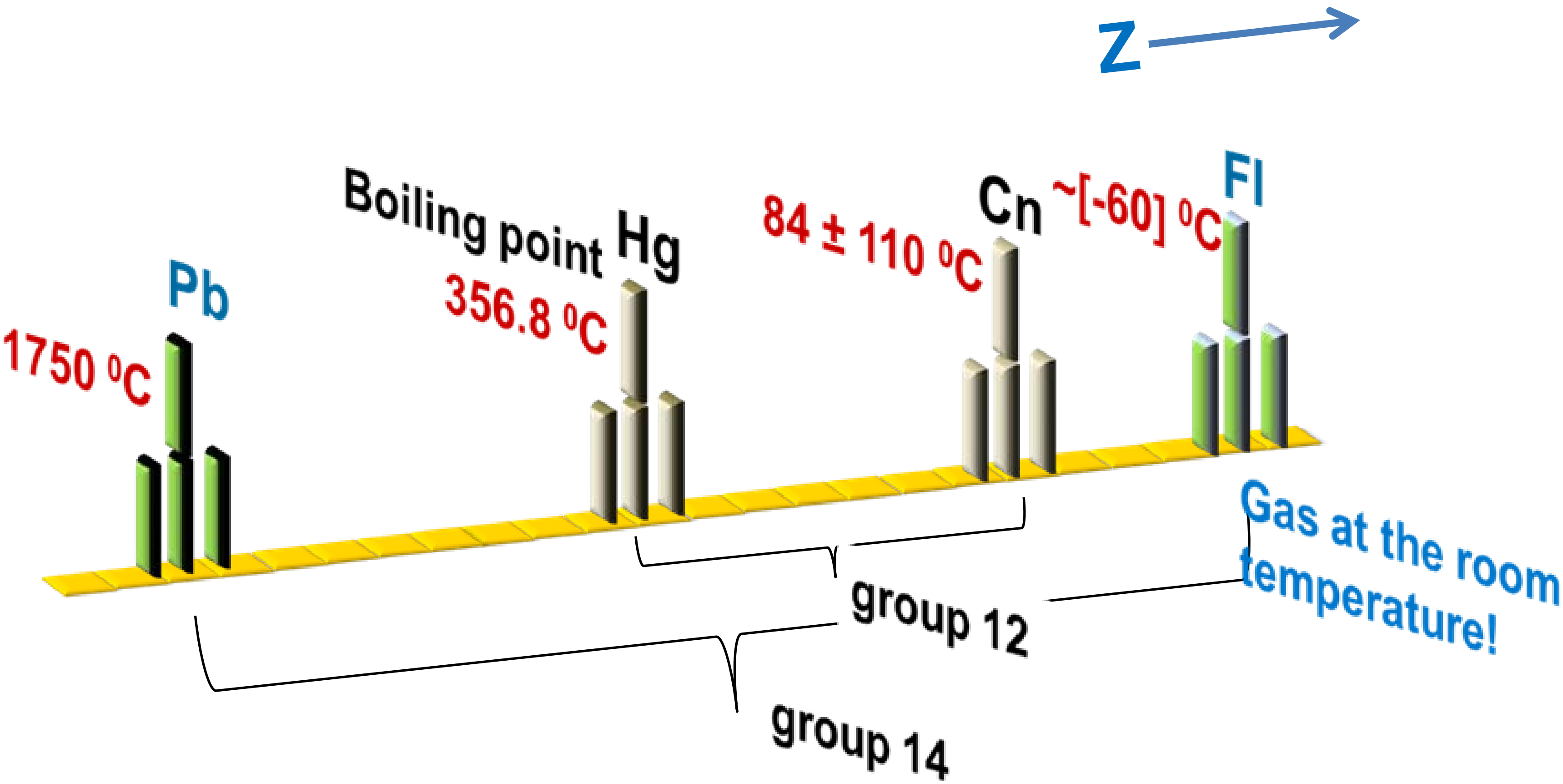


Thermo chromatography of the SHE and its light homologies on the gold surface

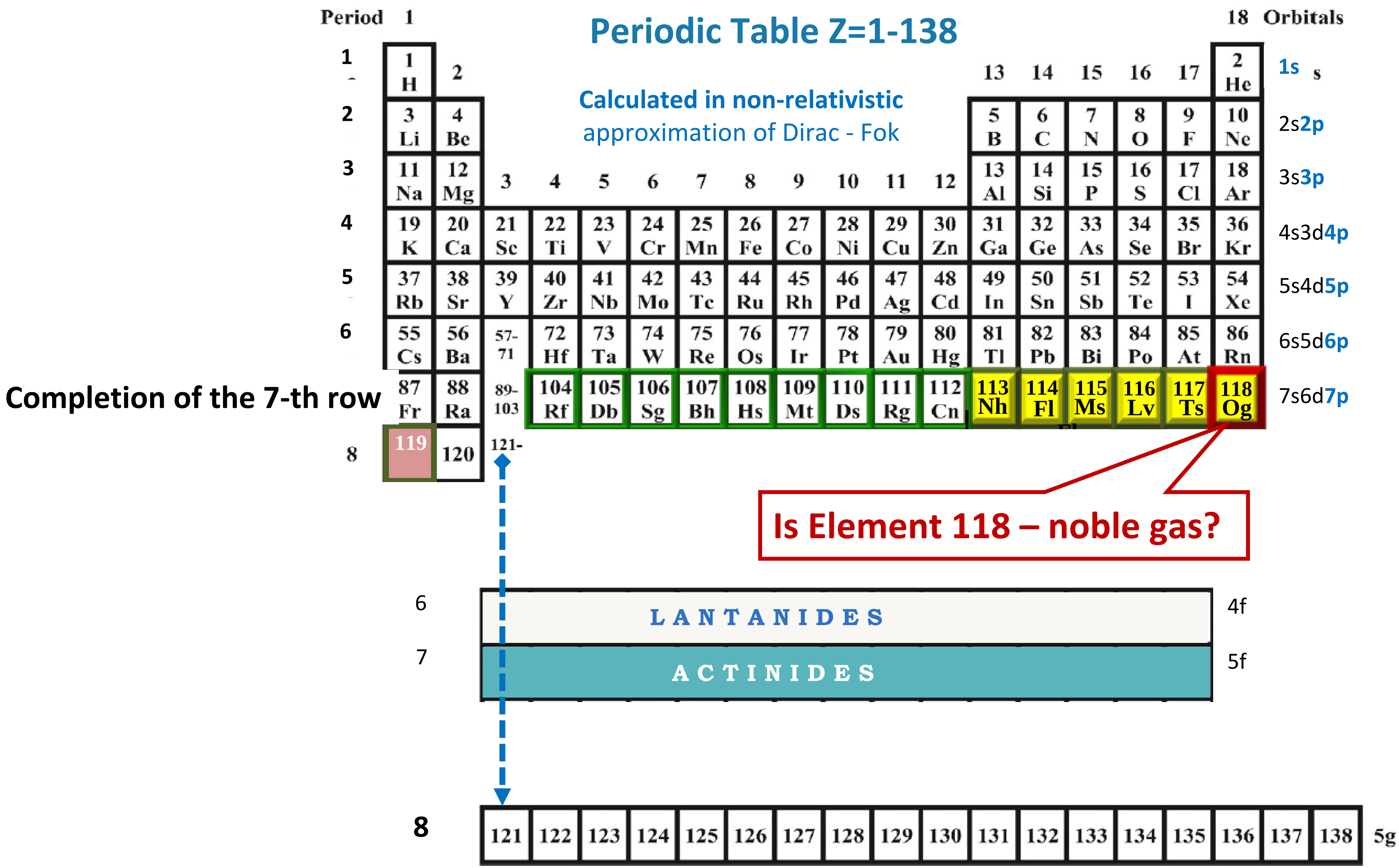


Thermo chromatography of the SHE

and its light homologies on the gold surface

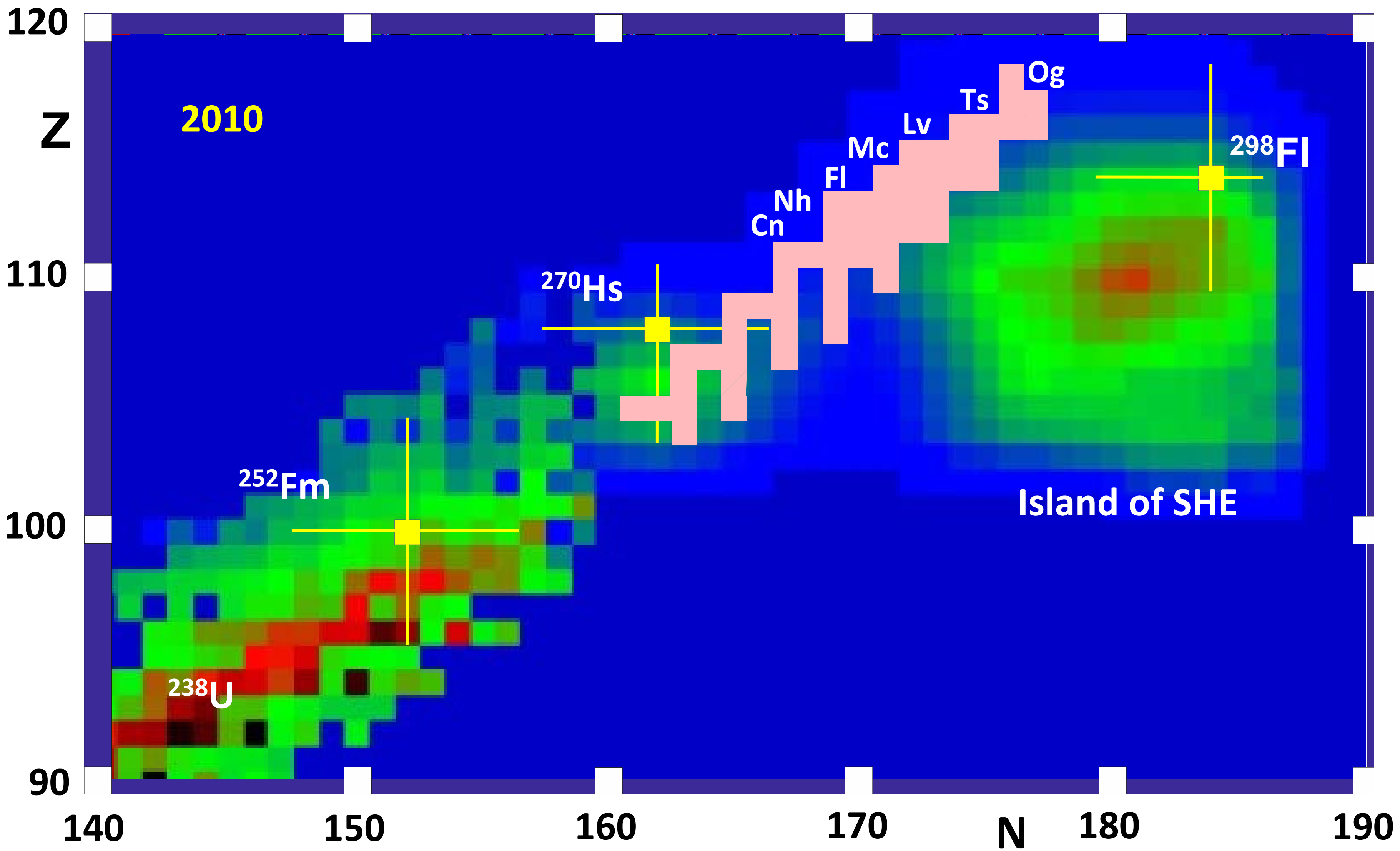


Yu. Oganessian. “Nuclear at the Mass Limit, Discovery of SHN” Seminar on NP of INPh April 4, 2017, MSU, Moscow

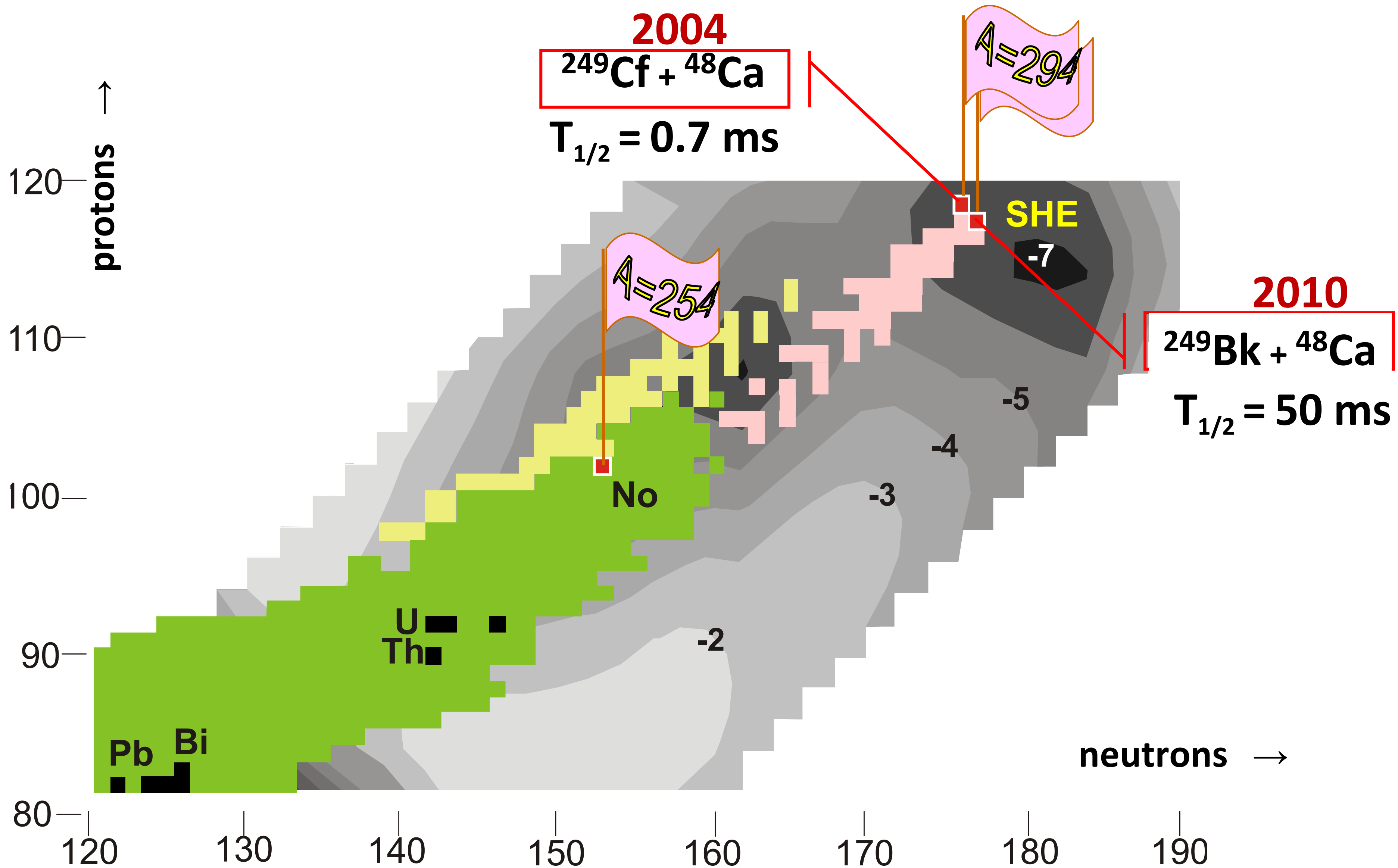


Yu. Oganessian. “Nuclear at the Mass Limit, Discovery of SHN” Seminar on NP of INPh April 4, 2017, MSU, Moscow

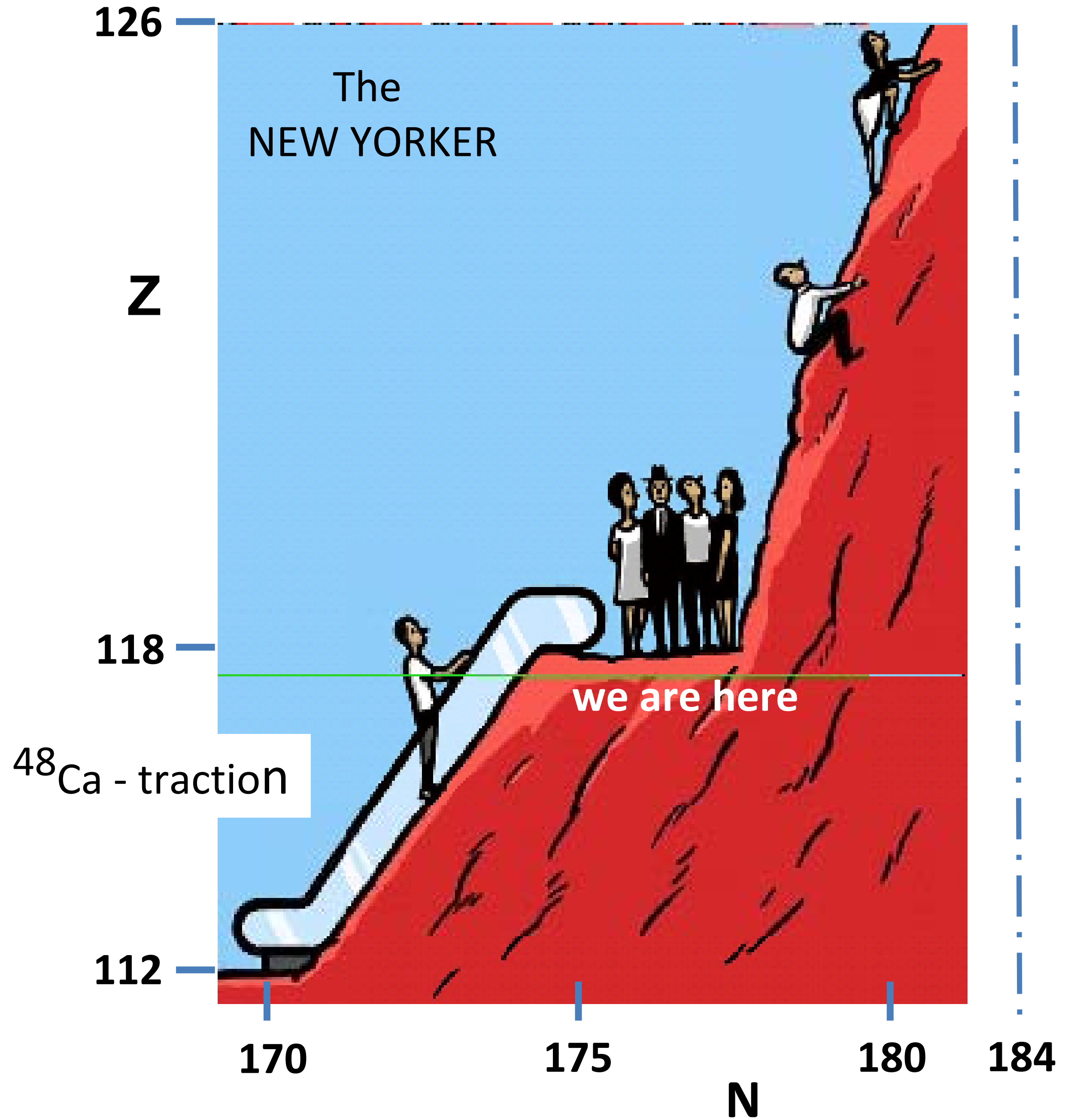
52 neutron-rich isotopes of the 15 heaviest elements were synthesized in ^{48}Ca-induced reactions



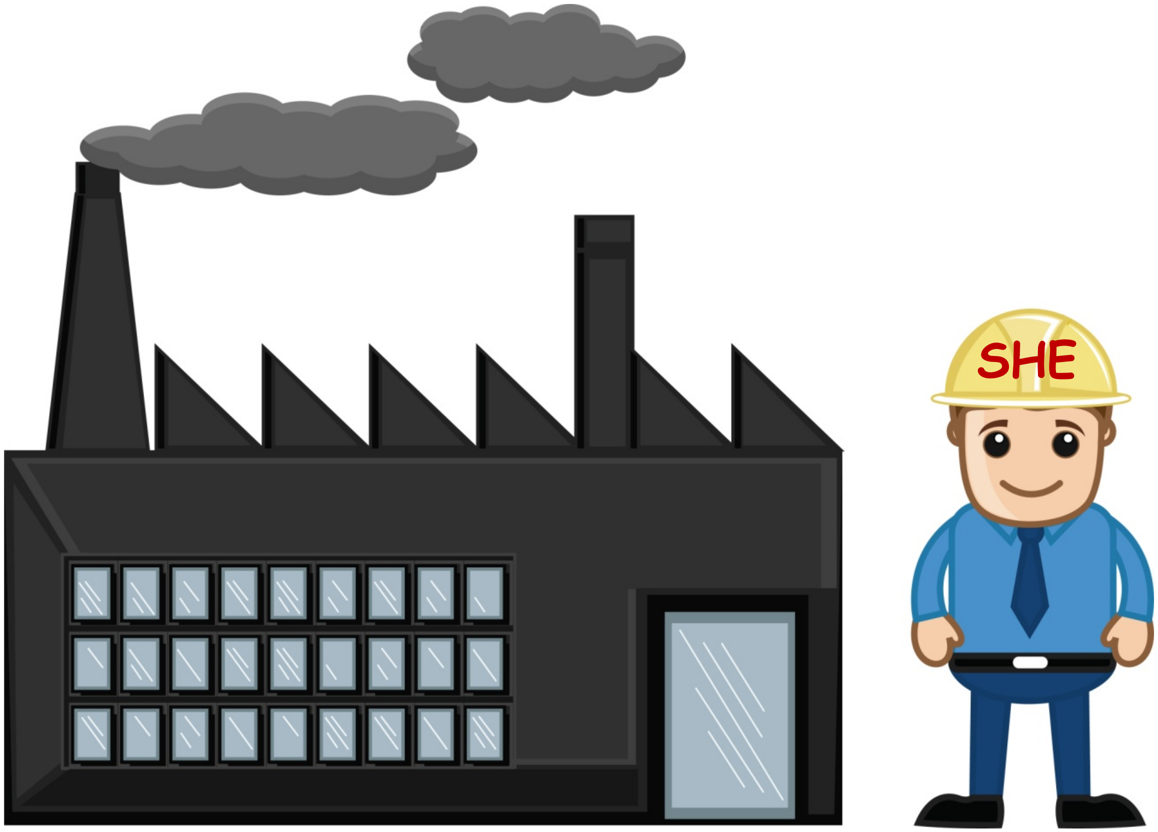
Yu. Oganessian. “Nuclear at the Mass Limit, Discovery of SHN” Seminar on NP of INPh April 4, 2017, MSU, Moscow



Yuri Oganessian. Discovery of SHN, Seminar of RIKEN, March 13, 2017, Tokyo, Japan


126
The
NEW YORKER
Z
118
we are here
48Ca - traction
112
170
175
180
184
N

Outcomes and the future



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

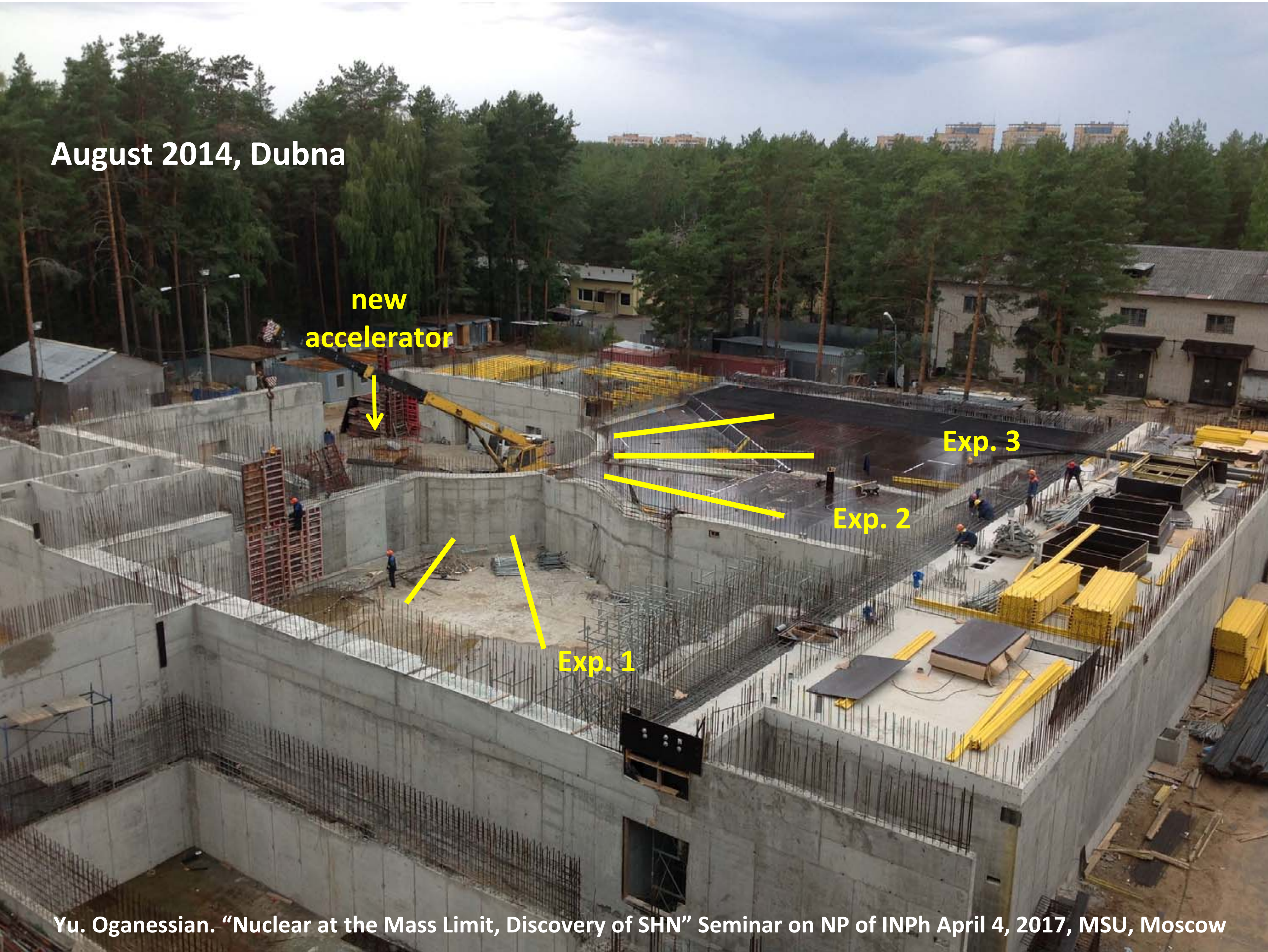
Factor 10-20

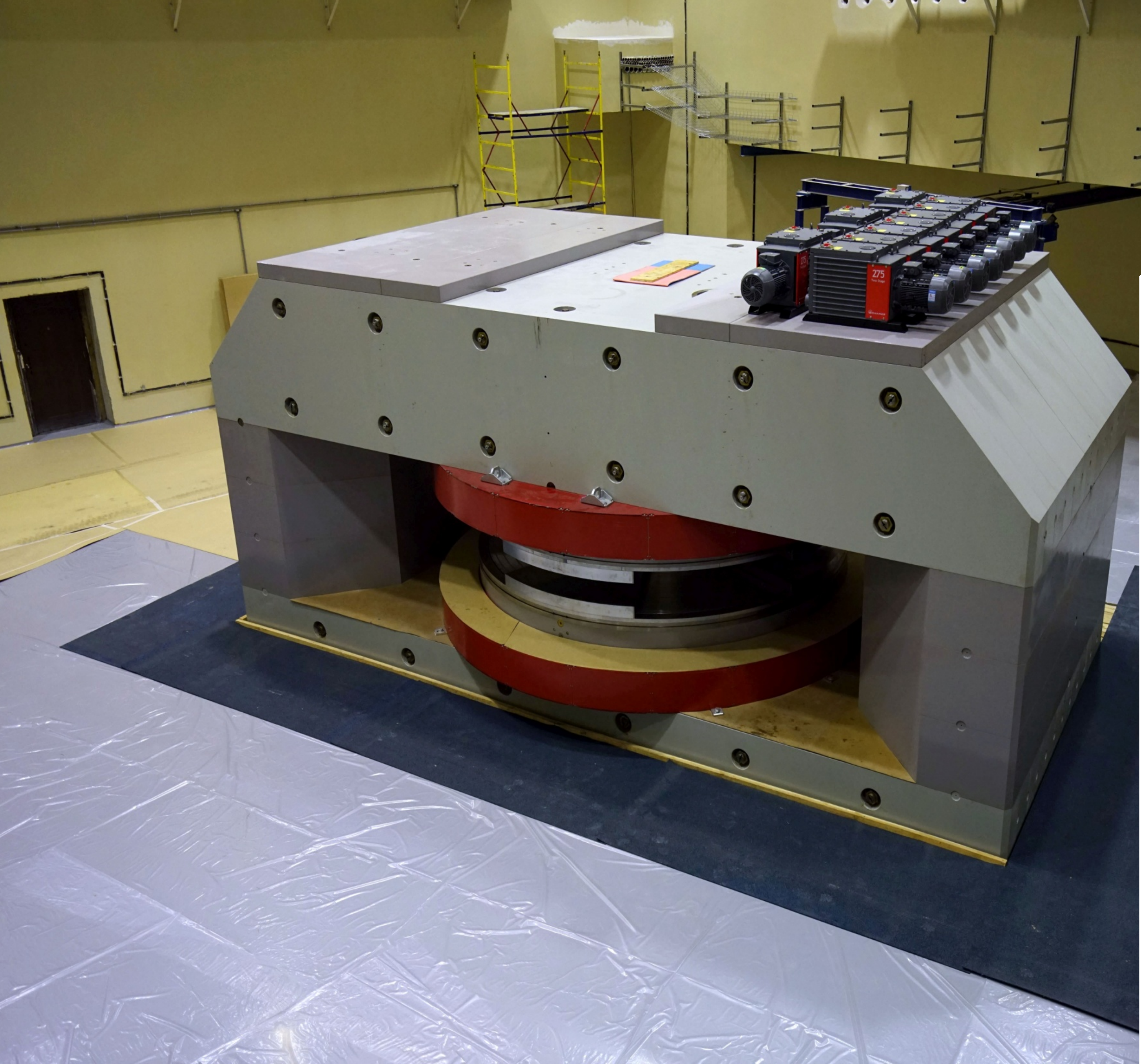
Depend of target durability

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



Projectile	Intensity Ion/s
^{20}Ne	$1\cdot10^{14}$
^{48}Ca	$6\cdot10^{13}$
^{50}Ti	$3\cdot10^{13}$
^{70}Zn	$2\cdot10^{13}$
^{86}Kr	$3\cdot10^{13}$
^{100}Mo	$2\cdot10^{12}$
^{124}Sn	$2\cdot10^{12}$
^{136}Xe	$2\cdot10^{13}$
^{208}Pb	$1\cdot10^{12}$
^{238}U	$1\cdot10^{11}$

1. Radiochemical Engineering Development Center
2. High-Flux Isotope Reactor
3. Nuclear Science and Technology Division
4. Chemical Sciences Division
5. Transportation and
6. Packaging Division

Target Team at Oak Ridge

More than 50 ORNL of staff contributed to the Bk-Cf production and separation

Collaboration

FLNR, JINR (Dubna)

ORNL (Oak-Ridge, USA)

LLNL (Livermore, USA)

ANL (Argonne, USA)

GSI (Darmstadt, Germany)

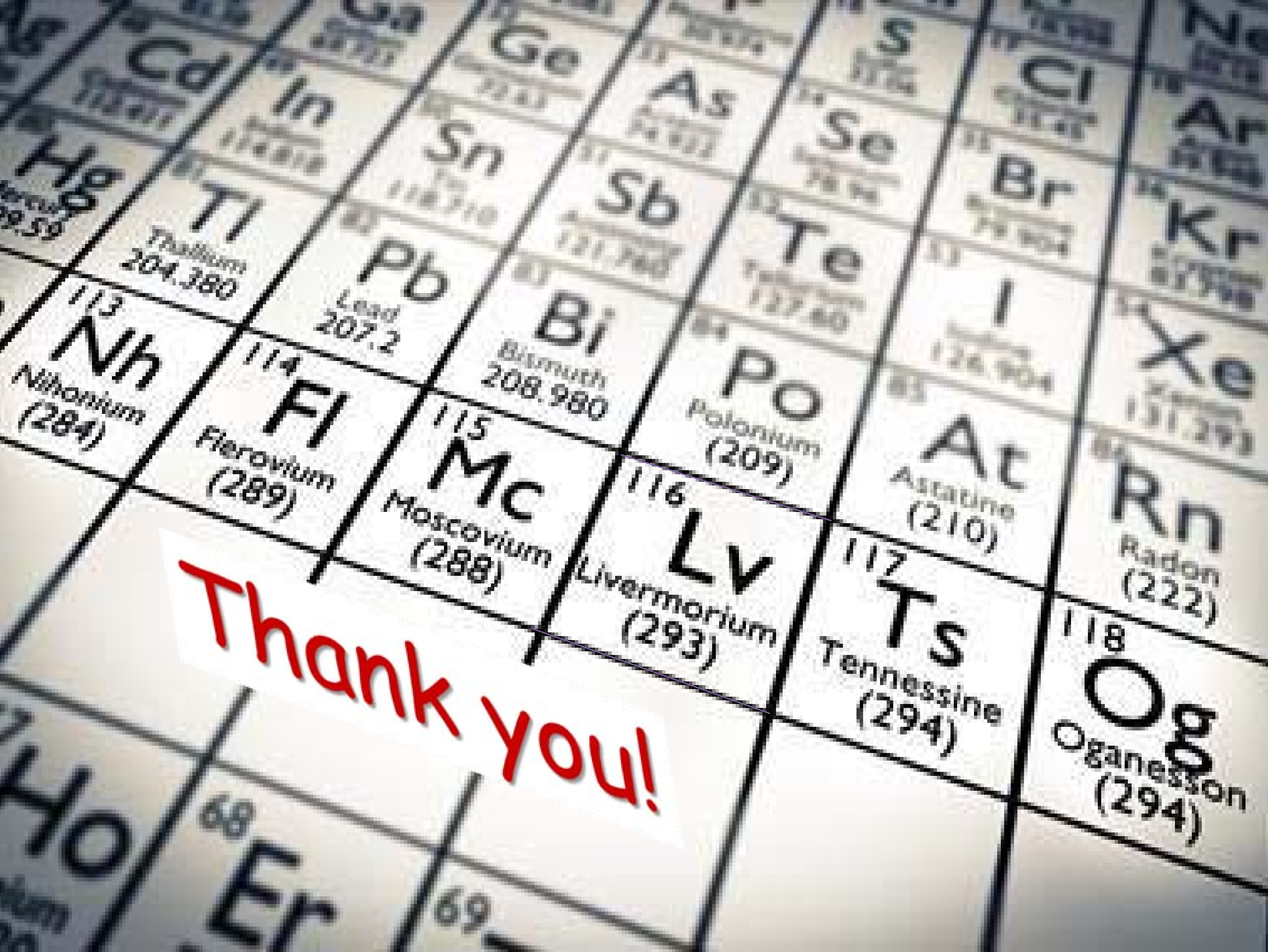
TAMU Cyclotron Institute (Texas, USA)

GANIL (Caen, France)

RIAR (Dimitrovgrad, Russia)

Vanderbilt University (Nashville, USA)

Knoxville University (Knoxville, USA)



Thank you!
Tl
Thallium
204.380
Pb
Lead
207.2
Bi
Bismuth
208.980
Po
Polonium
(209)
At
Astatine
(210)
Rn
Radon
(222)
113
Nh
Nihonium
(284)
114
Fl
Flerovium
(289)
115
Mc
Moscovium
(288)
116
Lv
Livermorium
(293)
117
Ts
Tennessine
(294)
118
Og
Oganesson
(294)
Ge
As
Se
Br
Kr
Xe
Sn
Sb
Te
I
Cl
S
In
Cd
Hg
Ho
Er
68
69