

*Explaining a scientific problem to high-rank officials,
try doing this not in the way it is correct, but in the way it is understandable.
It will be a noble lie*

Georgy FLEROV

Periodic table of elements and the Island of stability

Alexander Karpov

Flerov Laboratory of Nuclear Reactions, JINR, Dubna

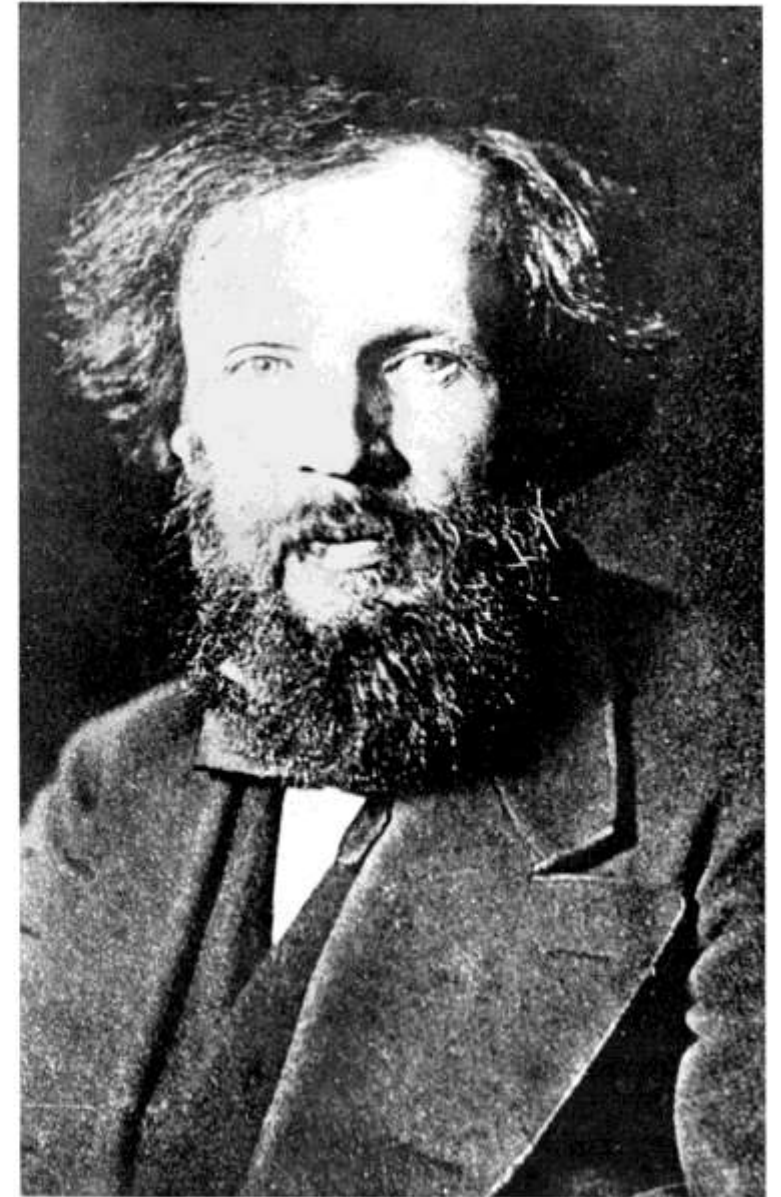
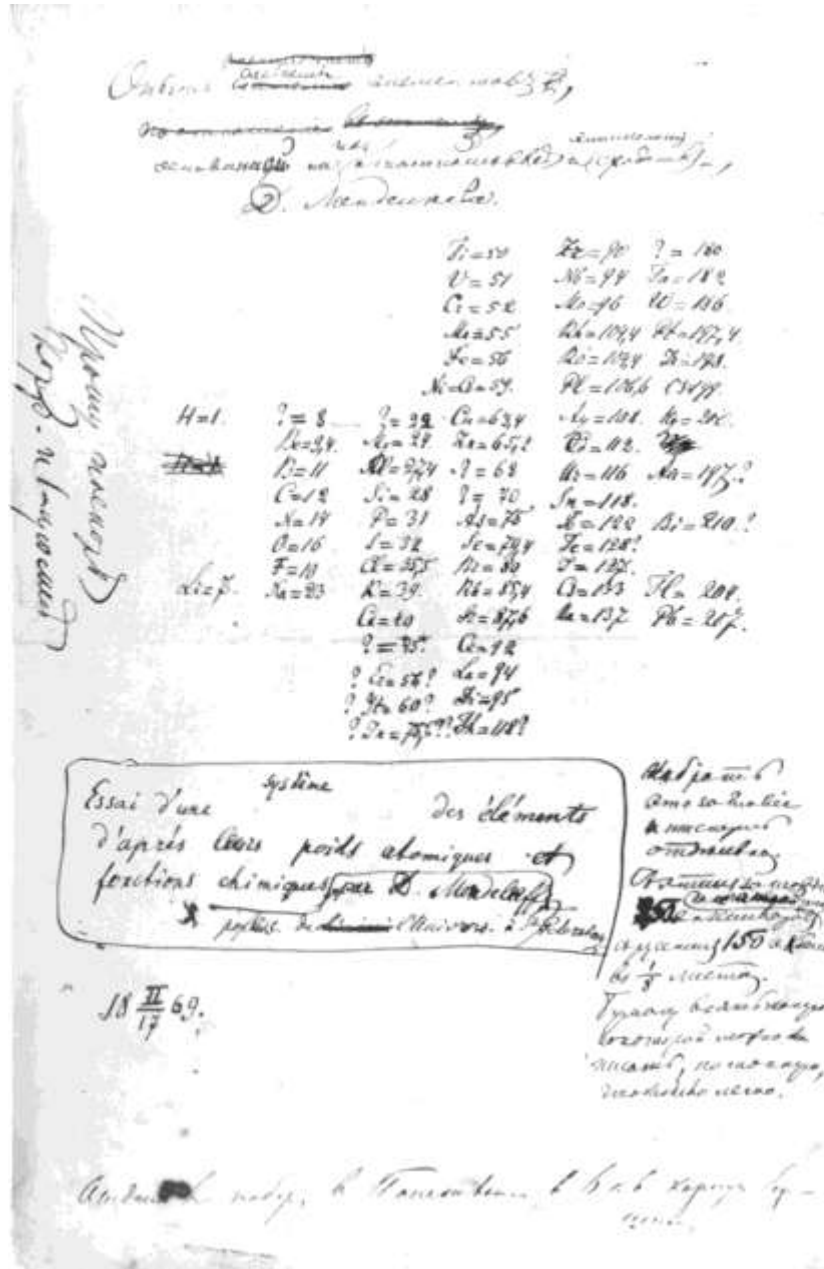


science bringing nations together

Mendeleev Periodic table of chemical elements (1869)



2019 International year of the Periodic table of chemical elements



Periodic table today



**Периодическая таблица элементов
Д.И. Менделеева
D.I. Mendeleev's Periodic Table of Elements**

1																	18
H Hydrogen	2											13	14	15	16	17	He Helium
Li Lithium	Be Beryllium	3	4	5	6	7	8	9	10	11	12	B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon
Na Sodium	Mg Magnesium	3	4	5	6	7	8	9	10	11	12	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur	Cl Chlorine	Ar Argon
K Potassium	Ca Calcium	Sc Scandium	Ti Titanium	V Vanadium	Cr Chromium	Mn Manganese	Fe Iron	Co Cobalt	Ni Nickel	Cu Copper	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium	Br Bromine	Kr Krypton
Rb Rubidium	Sr Strontium	Y Yttrium	Zr Zirconium	Nb Niobium	Mo Molybdenum	Tc Technetium	Ru Ruthenium	Rh Rhodium	Pd Palladium	Ag Silver	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon
Cs Cesium	Ba Barium	La Lanthanum	Hf Hafnium	Ta Tantalum	W Tungsten	Re Rhenium	Os Osmium	Ir Iridium	Pt Platinum	Au Gold	Hg Mercury	Tl Thallium	Pb Lead	Bi Bismuth	Po Polonium	At Astatine	Rn Radon
Fr Francium	Ra Radium	Ac Actinium	Rf Rutherfordium	Db Dubnium	Sg Seaborgium	Bh Bohrium	Hs Hassium	Mt Meitnerium	Ds Darmstadtium	Rg Roentgenium	Cn Copernicium	Nh Nihonium	Fl Flerovium	Mc Moscovium	Lv Livermorium	Ts Tennessine	Og Oganesson

Лантаноиды Lanthanoides

Ce Cerium	Pr Praseodymium	Nd Neodymium	Pm Promethium	Sm Samarium	Eu Europium	Gd Gadolinium	Tb Terbium	Dy Dysprosium	Ho Holmium	Er Erbium	Tm Thulium	Yb Ytterbium	Lu Lutetium
---------------------	---------------------------	------------------------	-------------------------	-----------------------	-----------------------	-------------------------	----------------------	-------------------------	----------------------	---------------------	----------------------	------------------------	-----------------------

Актиноиды Actinoides

Th Thorium	Pa Protactinium	U Uranium	Np Neptunium	Pu Plutonium	Am Americium	Cm Curium	Bk Berkelium	Cf Californium	Es Einsteinium	Fm Fermium	Md Mendelevium	No Nobelium	Lr Lawrencium
----------------------	---------------------------	---------------------	------------------------	------------------------	------------------------	---------------------	------------------------	--------------------------	--------------------------	----------------------	--------------------------	-----------------------	-------------------------

H Hydrogen

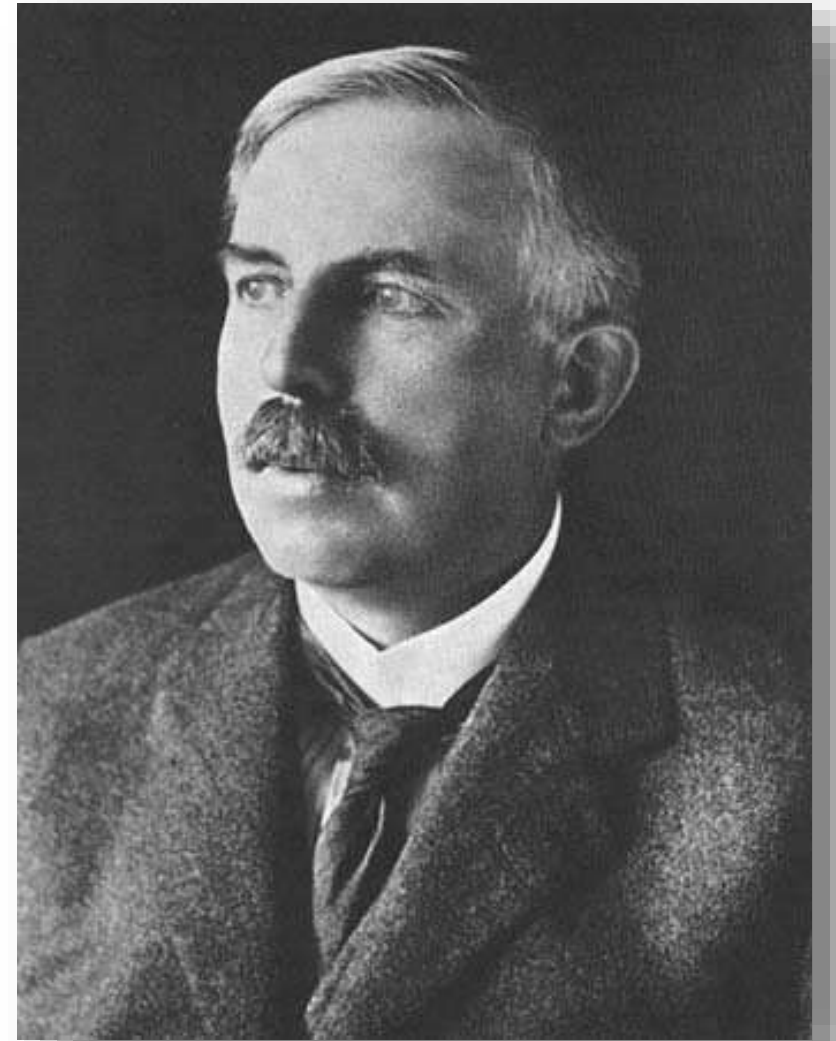
H - hydrogen / водород
 1.00794 - atomic weight / атомная масса
 1s¹ - electronic configuration / электронная конфигурация
 13.8065 - boiling point, °C / for solution present at 1 bar / температура кипения, °C / для раствора при давлении 1 бар
 20.14 - melting point, °C / melting temperature, °C
 253.67 - boiling point, °C / boiling temperature, °C

Nuclear reactions

1919: First nuclear reactions



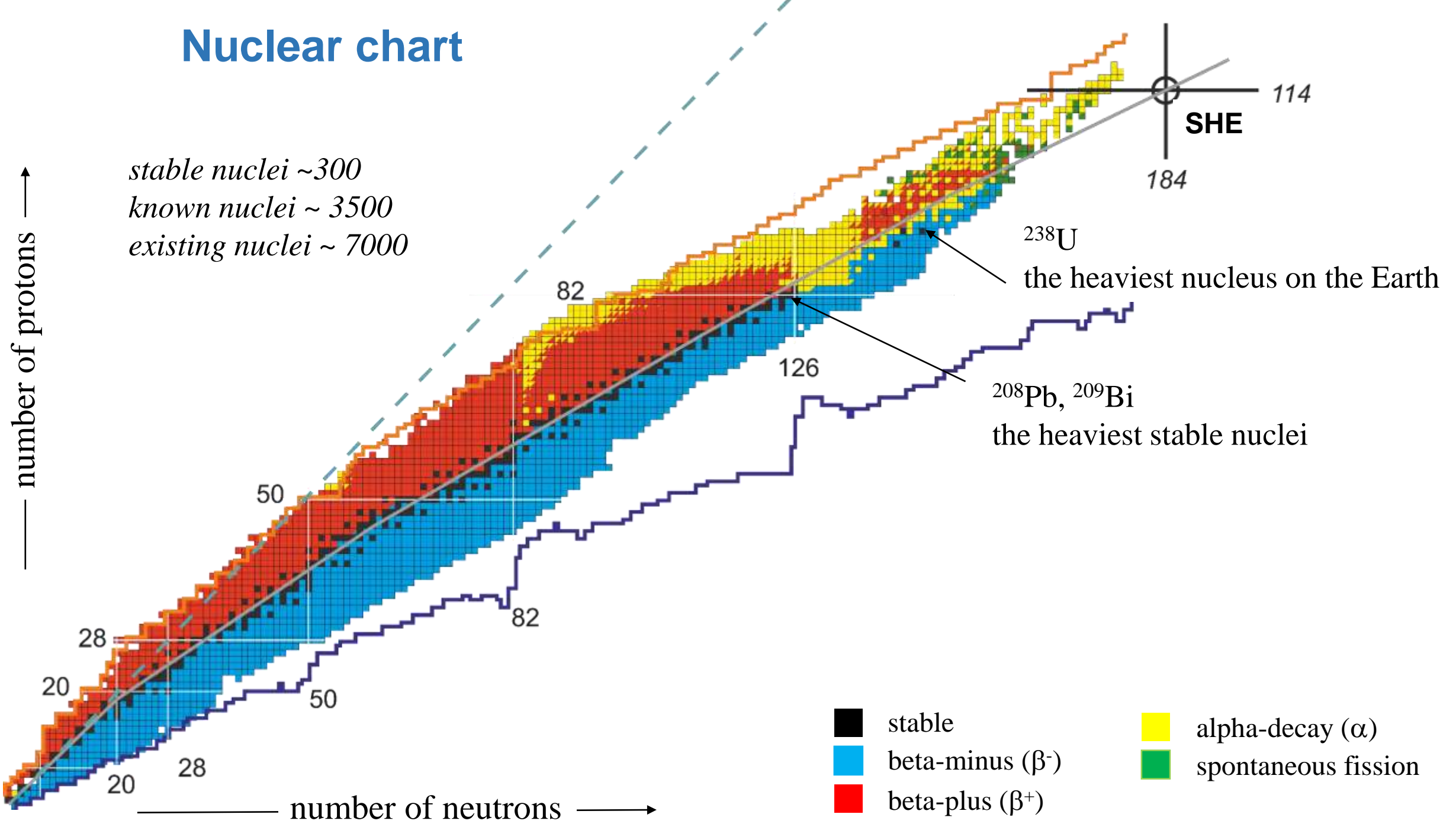
100 years ago mankind new how
to transform one nucleus (element) to another



Ernest Rutherford
(1871 – 1937)

Nuclear chart

stable nuclei ~300
known nuclei ~ 3500
existing nuclei ~ 7000



Abundance of Elements in the Universe

The 11 Greatest Unanswered Questions of Physics (National Research Council, NAS, USA, 2002):

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
- ...

2002-2019:

Discovery of gravitational waves →
first observation of gravitational waves
in a neutron star merge →
start of multimessage astronomy

future

understanding of astrophysical nucleosynthesis

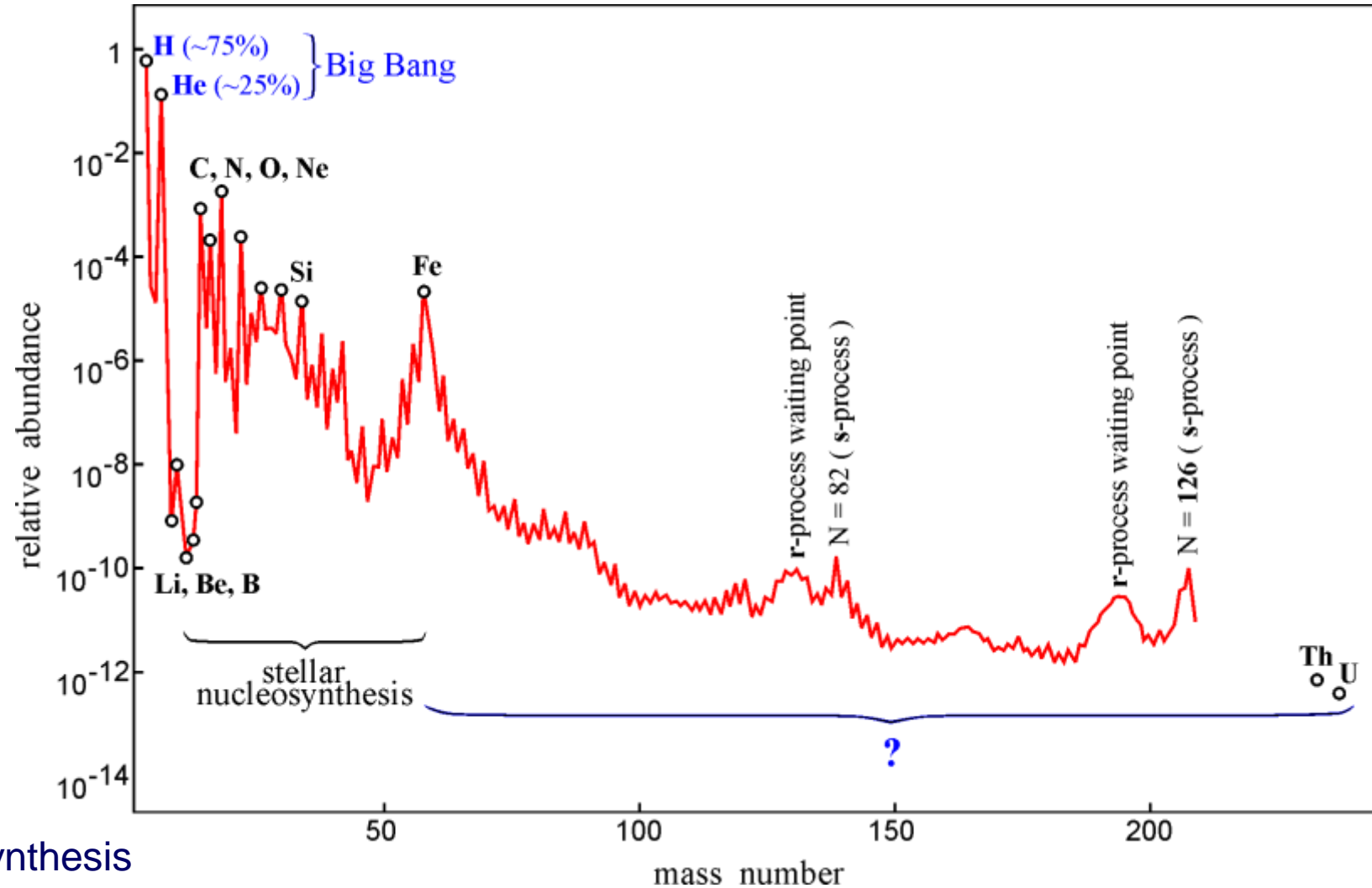


Chart of nuclei (upper part). Vision in 1950th

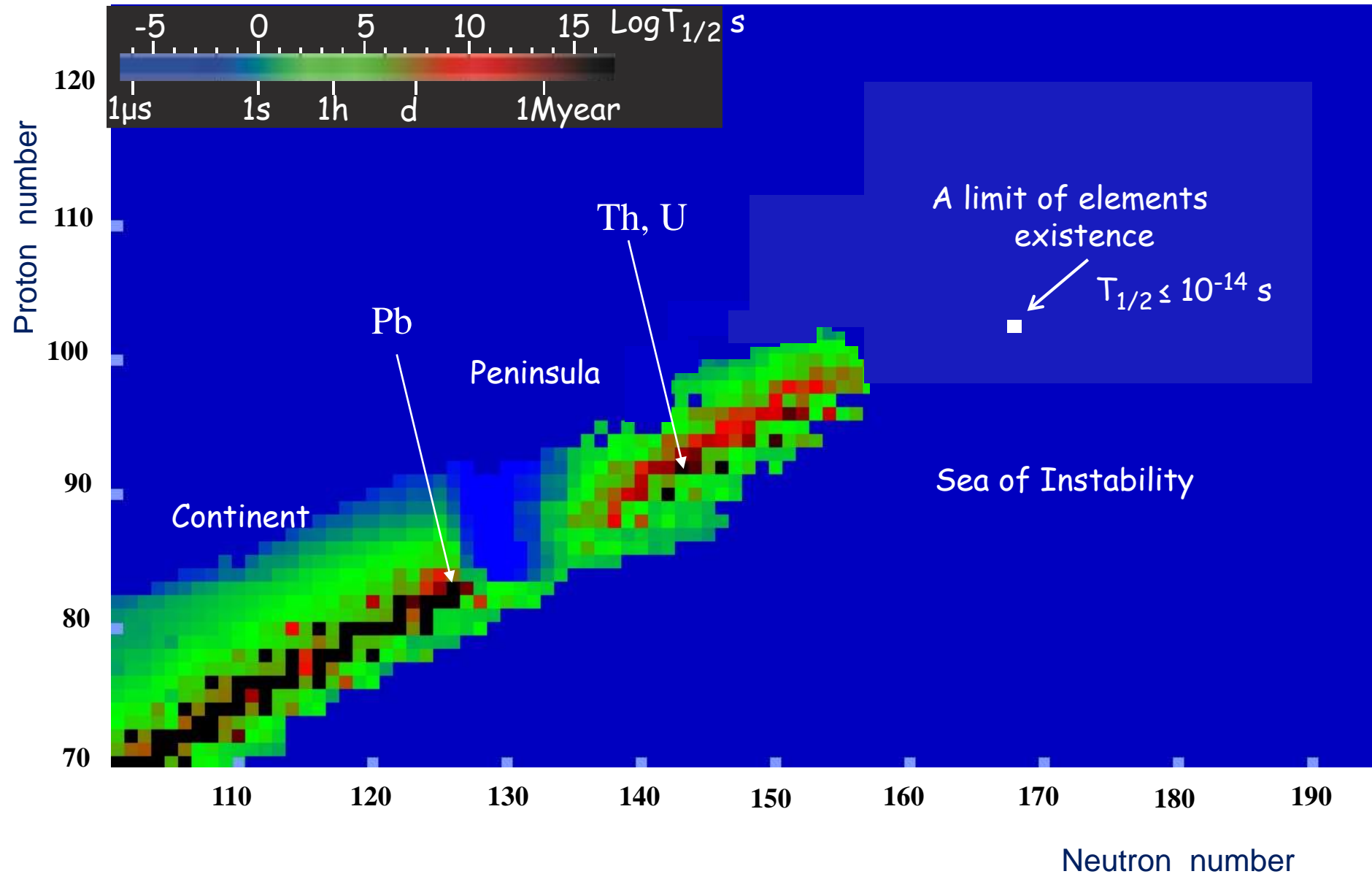
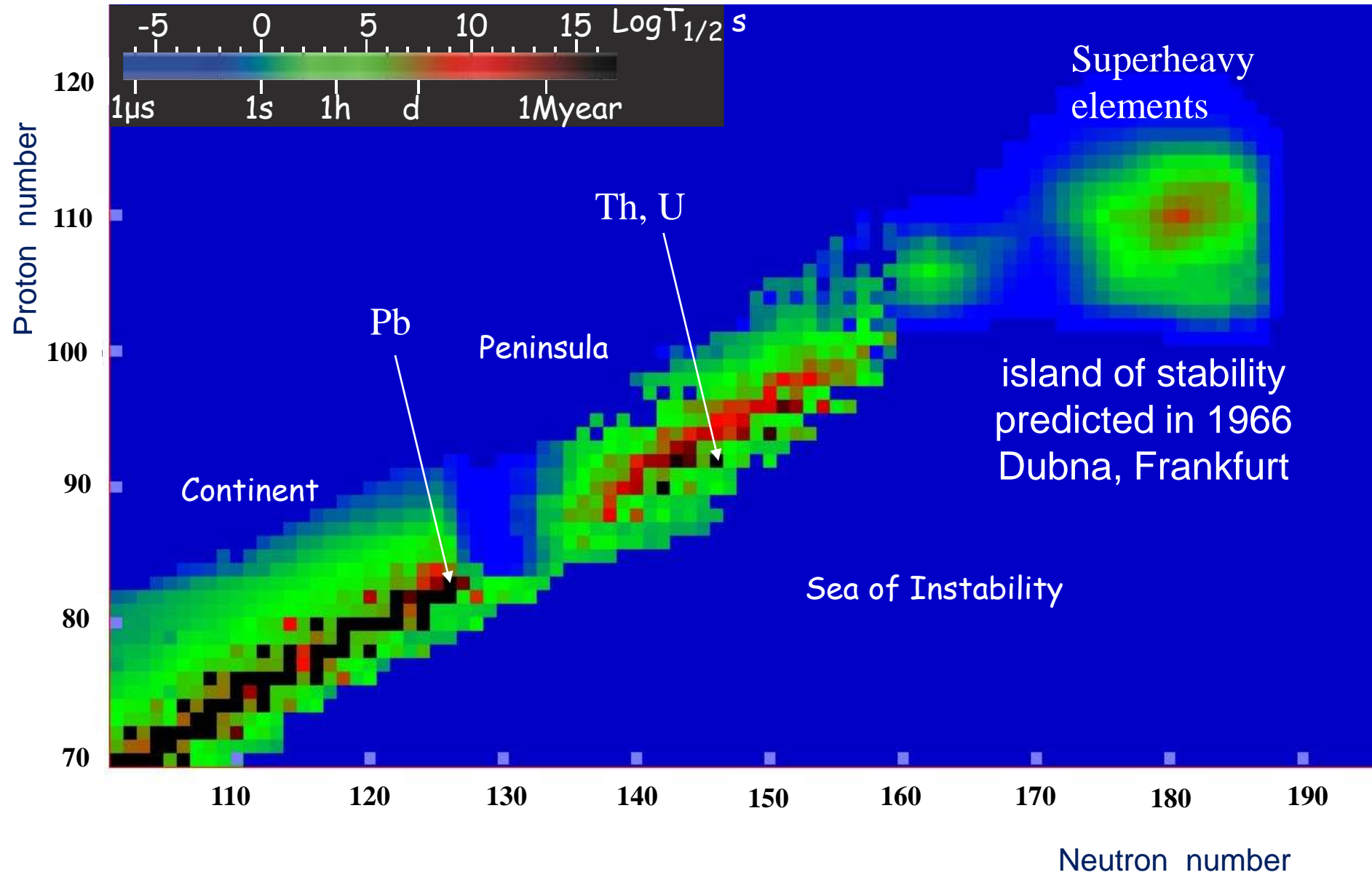


Chart of nuclei (upper part)



Experimenters rushed to find this Island

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

Search in nature:

earth/lunar objects, cosmic rays,

Artificial synthesis:

**high-flux reactor,
nuclear explosion,
powerful accelerator**

To develop setups:

**separator/detector,
spectrometers,
chemical methods, etc.**

Unfortunately in all attempts superheavy elements were not found

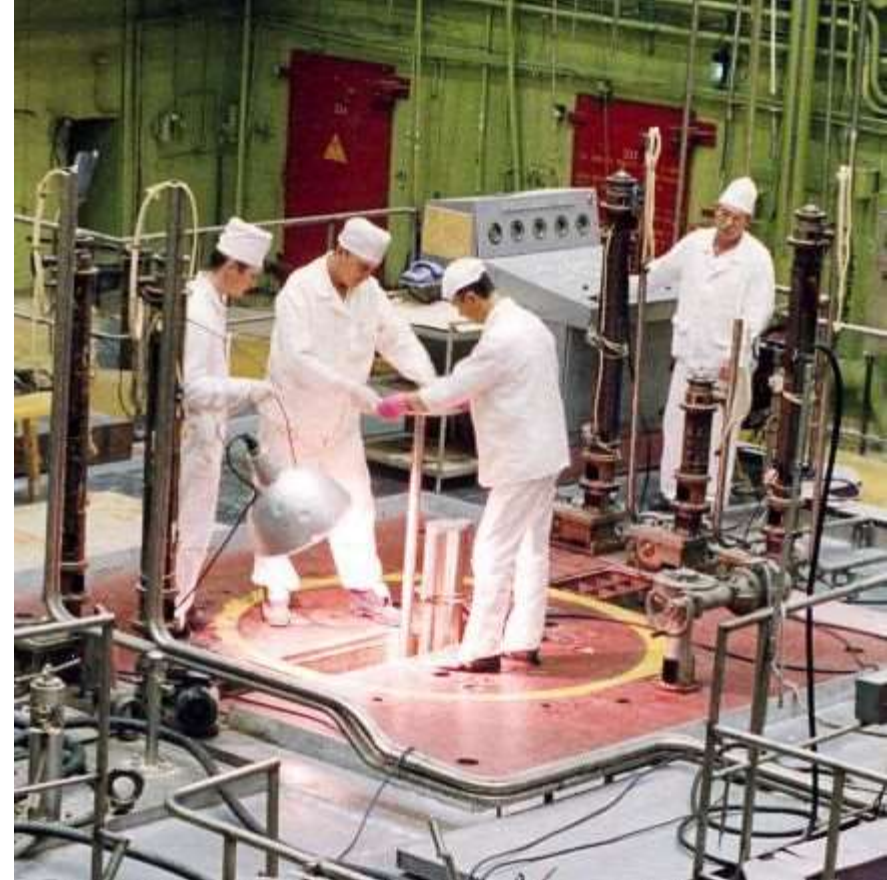
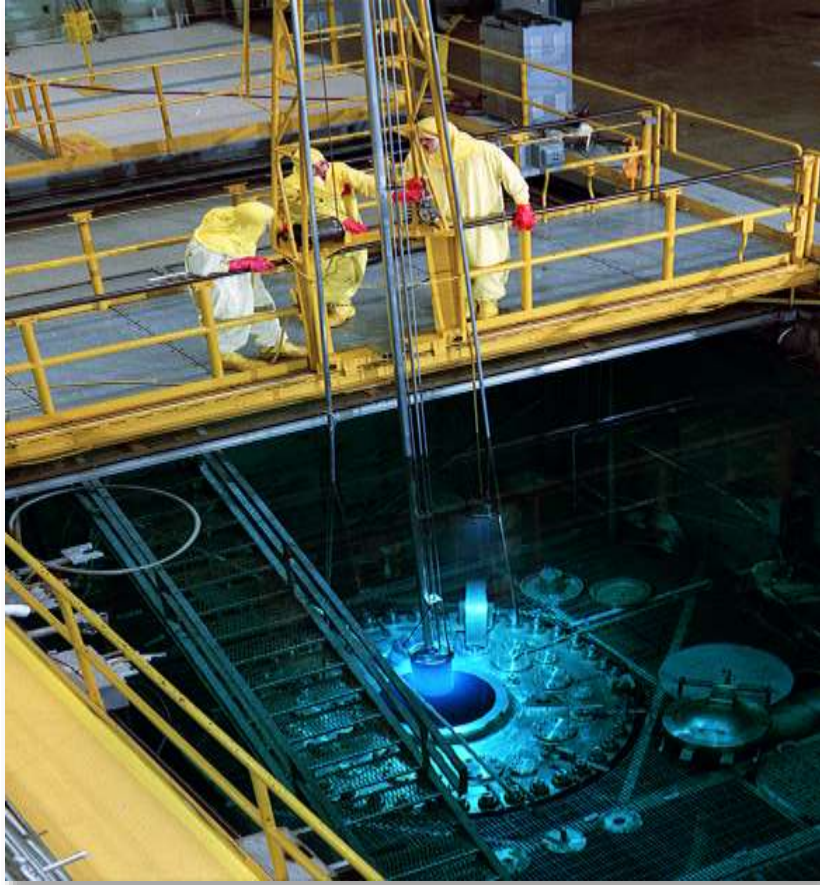
The problem of artificial synthesis of SHE is related with reaction of synthesis

**Dubna, beginning of 90th:
many times tried $^{48}\text{Ca} + \text{Act.}$ reactions are
the last hope to produce superheavies**

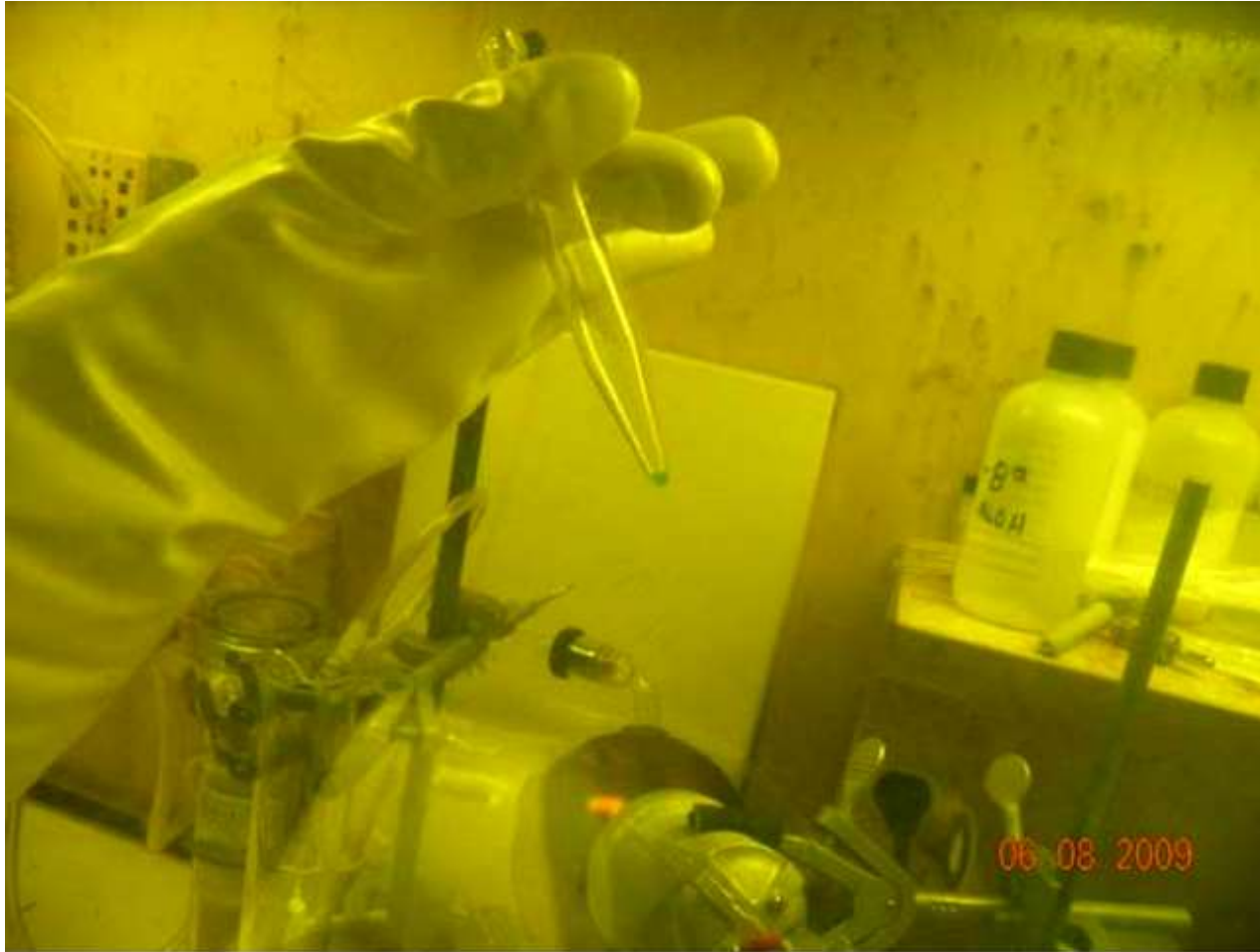
Reactors (target material)

HFIR, ORNL, Oak Ridge, USA, 85 MW

CM-3, IAR, Dimitrovgrad, Russia, 100 MW



22 mg of ^{249}Bk from Oak Ridge, Tennessee, USA



$\text{Bk}(\text{NO}_3)_3$ Product

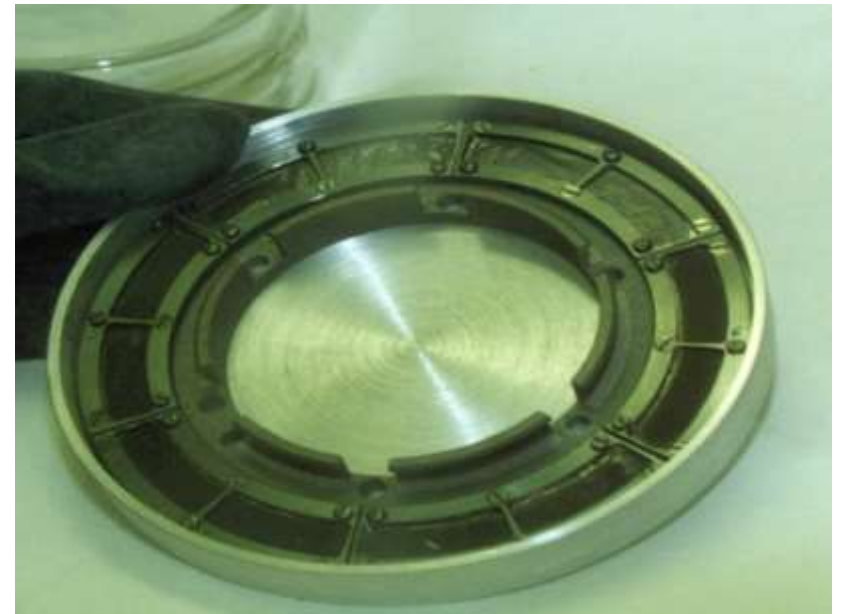
Annual production:

^{97}Bk , ^{98}Cf : 10th of mg;

^{99}Es : few μg ;

^{100}Es : < ng;

Target wheel (~15 mg)



ECR ion sources. Careful consumption of calcium

~2 gr. of ^{48}Ca

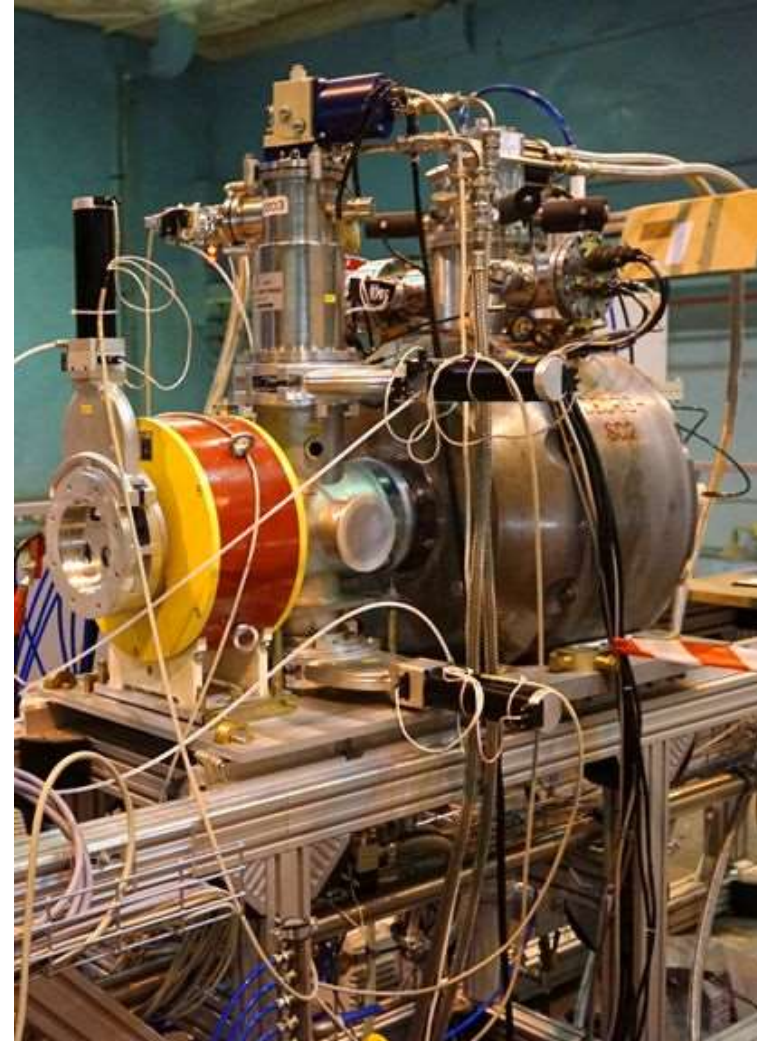
Ion source DECRIS-SC2



Consumption: 0.5-0.8 mg/h

Annual production: 10-12 grams

“Elektrokhimpribor”, Lesnoy, Sverdlovsk region, Russia



U-400 cyclotron at FLRN, JINR



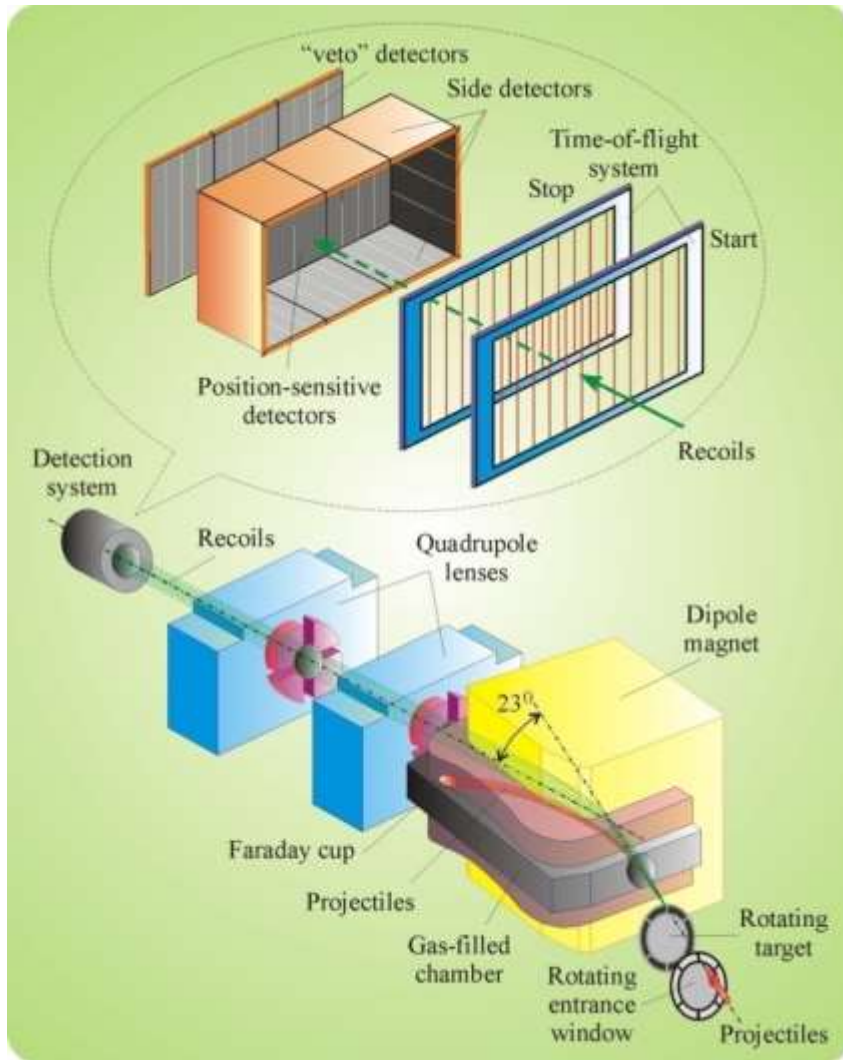
Beam of ^{48}Ca

Intensity:
 $6 \cdot 10^{12}$ ion/s

Energy:
~300 MeV

Speed:
10% speed of light

Gas-filled separator



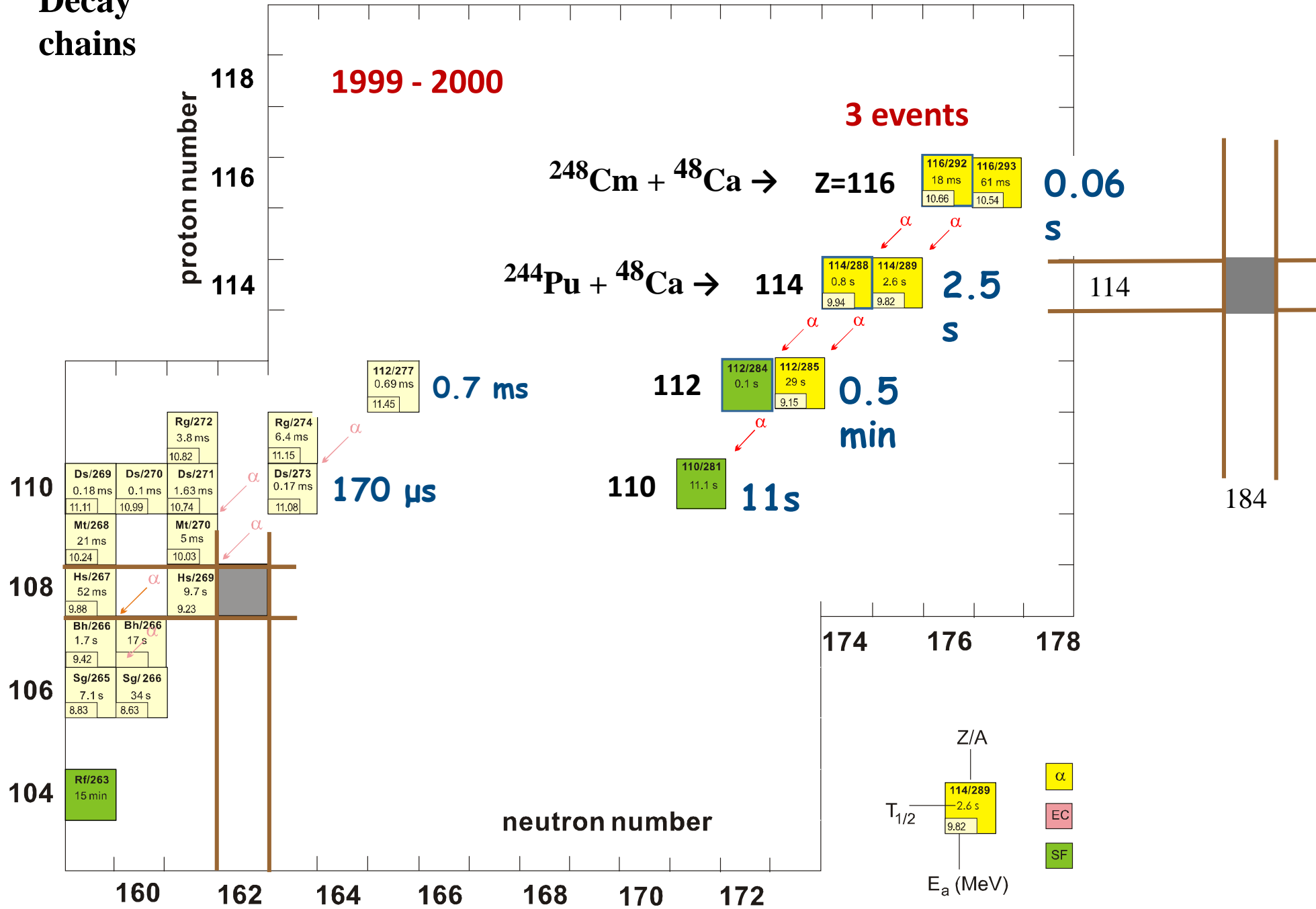
Looking for:
~1 event/day

Without separator:
 10^{13} events/s

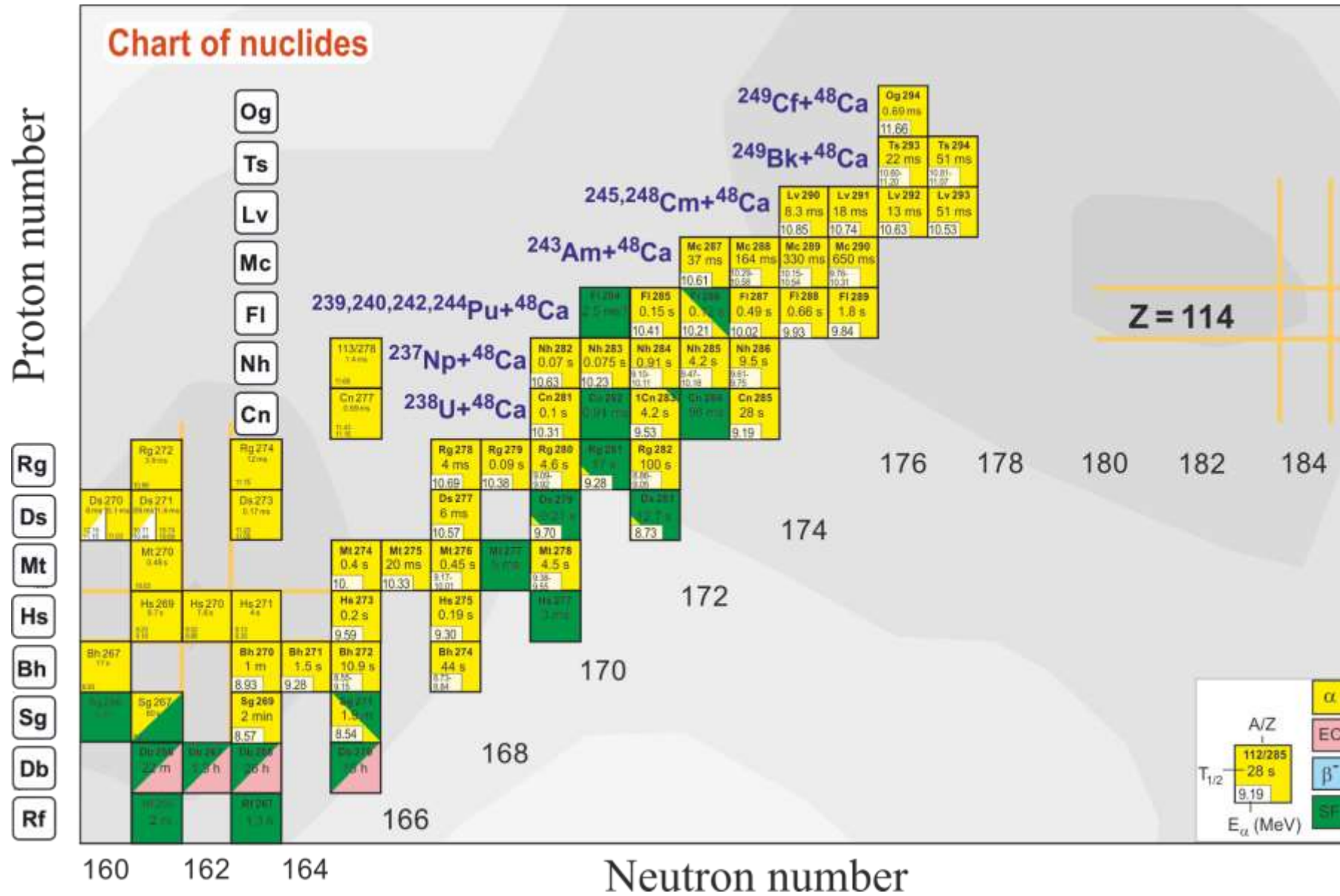
With separator:
100 events/s

Collecting efficiency:
~30%

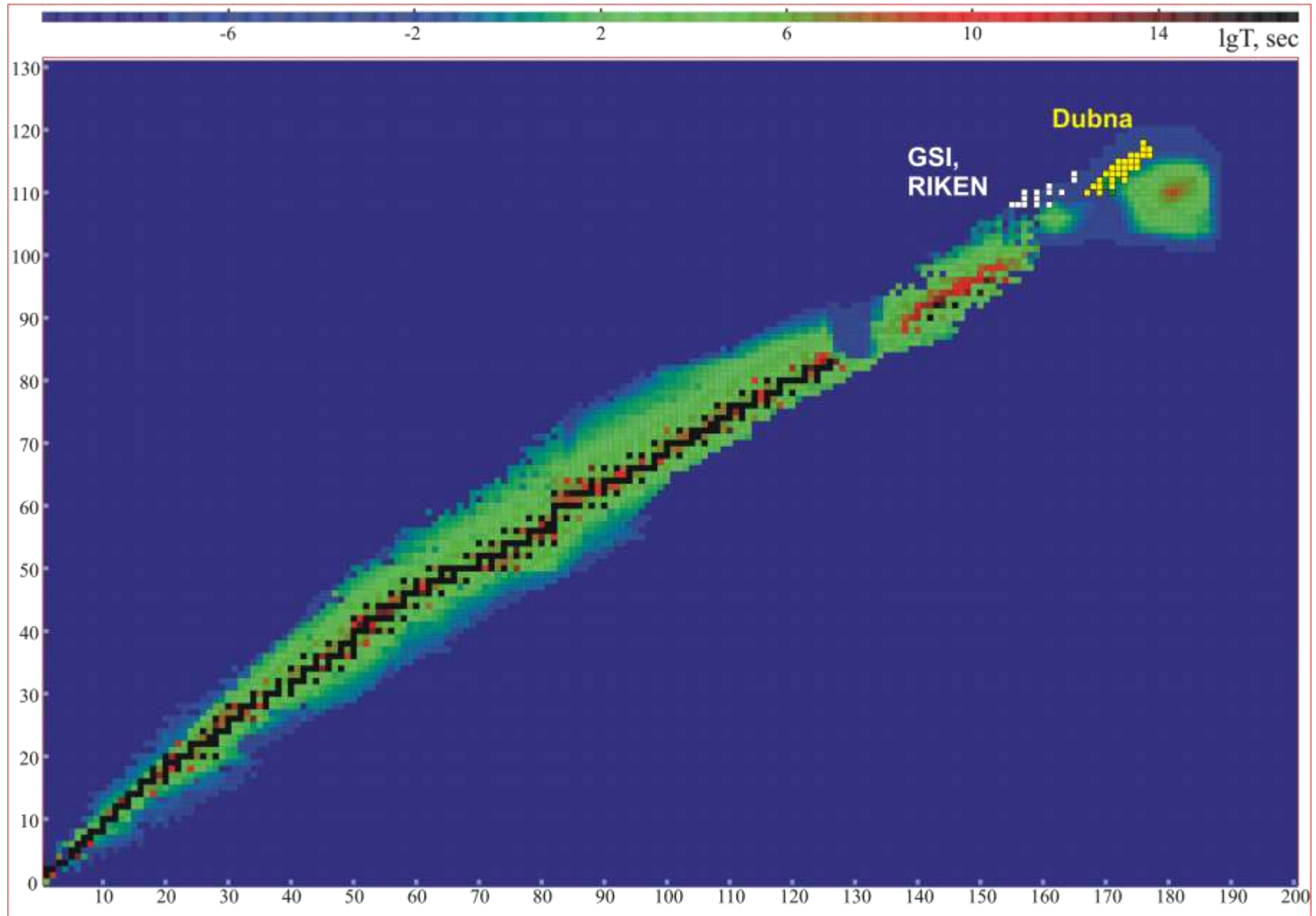
Decay chains



Synthesis of Superheavy Nuclei (*since 1999*)



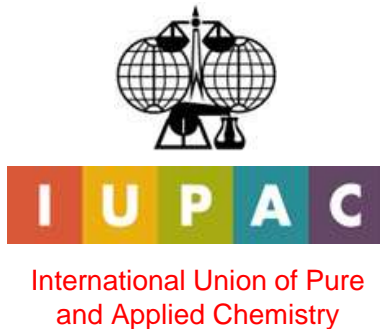
Approaching the island of stability



Confirmations

(2007-2014)

A, Z	Setup	Laboratory	Published
²⁸³112	SHIP	GSI Darmstadt	Eur. Phys. J. A 32, 251 (2007)
²⁸³112	COLD	PSI-FLNR (JINR)	NATURE 447, 72 (2007)
^{286, 287}114	BGS	LRNL (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. A 48: 62 (2012)
^{287, 288}115	TASCA	GSI – Mainz	P.R. Lett. 111, 112502 (2013)
²⁹⁴117	TASCA	GSI-Mainz	P.R. Lett. 112, 172501 (2014)



May 2012:

Official approval of the name *Flerovium* for element **114**
and the name *Livermorium* for element **116**

30th December 2015:

Approval of the discovery of new elements **113, 115, 117, and 118**

- element **113**: RIKEN (Japan)
- elements **115** and **117**: JINR (Dubna) - LLNL (USA) – ORNL (USA) collaboration
- element **118**: JINR (Dubna) – LLNL collaboration.

28th November 2016:

IUPAC formally approved names and symbols of new elements:

Nihonium (Nh) for element **113**,

Moscovium (Mc) for element **115**,

Tennessine (Ts) for element **117**, and

Oganesson (Og) for element **118**.



G. Flerov

Флеровий 114	Московский 115	Ливерморий 116	Теннессин 117	Оганесон 118
Fl	Mc	Lv	Ts	Og
Flerovium	Moscovium	Livermorium	Tennessine	Oganesson

All these elements were synthesized for the first time at the U-400 accelerator complex of the Flerov Laboratory of Nuclear Reactions of JINR.



Yu. Oganessian

In pursuit of new elements



Berkeley Lab

USA, California, Berkeley:

101(Md), **102(No)**, **103(Lr)**, **104 (Rf)**, **105 (Db)**, **106 (Sg)**

G. Seaborg, A. Ghiorso, et al.

Dubna: 1964 - 1975 — **102 (No)**, **103 (Lr)**, **104 (Rf)**, **105 (Dubnium)**, **106 (Sg)**, **107 (Bh)**, **108 (Hs)**

G.N. Flerov, Yu.Ts. Oganessian, et al.



2000 — **114 (Fl)**, 2002 — **116 (Lv)**, 2003 — **113 (Nh)**, **118 (Og)**, 2009 — **115 (Mc)**, **117 (Ts)**

Yu.Ts. Oganessian, et al.



Germany, Darmstadt, GSI:

1989 - 2000 — **107 (Bh)**, **108 (Hs)**, **109 (Mt)**, **110 (Ds)**, **111 (Rg)**, **112 (Cn)**

P. Armbruster, G. Münzenberg, S. Hofmann, et al.



Japan, Tokyo, RIKEN:

2003 - 2012 — **110 (Ds)**, **111 (Rg)**, **112 (Cn)**, **113 (Nh)**

K. Morita, et al.

Mendeleev's Table Today



**Периодическая таблица элементов
Д.И. Менделеева**
D.I. Mendeleev's Periodic Table of Elements

1																	18
H 1.00794 Hydrogen	2											13	14	15	16	17	He 4.0026 Helium
Li 6.941 Lithium	Be 9.01218 Beryllium	3	4	5	6	7	8	9	10	11	12	B 10.811 Boron	C 12.011 Carbon	N 14.007 Nitrogen	O 15.999 Oxygen	F 18.998 Fluorine	Ne 20.179 Neon
Na 22.98976928 Sodium	Mg 24.304 Magnesium	3	4	5	6	7	8	9	10	11	12	Al 26.9815385 Aluminum	Si 28.0855 Silicon	P 30.973761508 Phosphorus	S 32.06 Sulfur	Cl 35.45 Chlorine	Ar 39.948 Argon
K 39.0983 Potassium	Ca 40.078 Calcium	Sc 44.955912 Scandium	Ti 47.867 Titanium	V 50.9415 Vanadium	Cr 51.9961 Chromium	Mn 54.938044 Manganese	Fe 55.845 Iron	Co 58.933195 Cobalt	Ni 58.6934 Nickel	Cu 63.546 Copper	Zn 65.38 Zinc	Ga 69.723 Gallium	Ge 72.630 Germanium	As 74.921595 Arsenic	Se 78.96 Selenium	Br 79.904 Bromine	Kr 83.80 Krypton
Rb 85.4678 Rubidium	Sr 87.62 Strontium	Y 88.905848 Yttrium	Zr 91.224 Zirconium	Nb 92.90638 Niobium	Mo 95.94 Molybdenum	Tc [98] Technetium	Ru 101.07 Ruthenium	Rh 102.90550 Rhodium	Pd 106.42 Palladium	Ag 107.8682 Silver	Cd 112.411 Cadmium	In 114.818 Indium	Sn 118.710 Tin	Sb 121.757 Antimony	Te 127.60 Tellurium	I 126.905 Iodine	Xe 131.29 Xenon
Cs 132.90545196 Cesium	Ba 137.327 Barium	La 138.90547 Lanthanum	Hf 178.49 Hafnium	Ta 180.94788 Tantalum	W 183.84 Tungsten	Re 186.207 Rhenium	Os 190.23 Osmium	Ir 192.222 Iridium	Pt 195.084 Platinum	Au 196.966569 Gold	Hg 200.59 Mercury	Tl 204.3843 Thallium	Pb 207.2 Lead	Bi 208.980389 Bismuth	Po [209] Polonium	At [210] Astatine	Rn [222] Radon
Fr [223] Francium	Ra [226] Radium	Ac [227] Actinium	Rf [261] Rutherfordium	Db [262] Dubnium	Sg [263] Seaborgium	Bh [264] Bohrium	Hs [265] Hassium	Mt [266] Meitnerium	Ds [268] Darmstadtium	Rg [269] Roentgenium	Cn [284] Copernicium	Nh [285] Nihonium	Fl [286] Flerovium	Mc [287] Moscovium	Lv [288] Livermorium	Ts [289] Tennessine	Og [294] Oganesson

Лантаноиды Lanthanoides

Ce 140.12 Cerium	Pr 140.90765 Praseodymium	Nd 144.24 Neodymium	Pm [145] Promethium	Sm 150.36 Samarium	Eu 151.964 Europium	Gd 157.25 Gadolinium	Tb 158.92534 Terbium	Dy 162.50 Dysprosium	Ho 164.93032 Holmium	Er 167.259 Erbium	Tm 168.93048 Thulium	Yb 173.054 Ytterbium	Lu 174.967 Lutetium
-------------------------------	--	----------------------------------	----------------------------------	---------------------------------	----------------------------------	-----------------------------------	-----------------------------------	-----------------------------------	-----------------------------------	--------------------------------	-----------------------------------	-----------------------------------	----------------------------------

Актиноиды Actinoides

Th 232.0377 Thorium	Pa 231.036888 Protactinium	U 238.02891 Uranium	Np [237] Neptunium	Pu [244] Plutonium	Am [243] Americium	Cm [247] Curium	Bk [247] Berkelium	Cf [251] Californium	Es [252] Einsteinium	Fm [257] Fermium	Md [258] Mendelevium	No [259] Nobelium	Lr [260] Lawrencium
----------------------------------	---	----------------------------------	---------------------------------	---------------------------------	---------------------------------	------------------------------	---------------------------------	-----------------------------------	-----------------------------------	-------------------------------	-----------------------------------	--------------------------------	----------------------------------

H 1.00794 Hydrogen

H - hydrogen / водород
 1.00794 - atomic weight / атомный вес
 [a] - isotopic composition / изотопный состав
 [c] - electron configuration / электронная конфигурация
 [e] - electron configuration of ion / электронная конфигурация иона
 [t] - boiling temperature / температура кипения
 [m.p.] - melting temperature / температура плавления
 [d] - density / плотность
 [c.p.] - critical temperature / критическая температура
 [c.p.] - critical pressure / критическое давление
 [c.p.] - boiling temperature / температура кипения

**10 of 18 elements synthesized since 1955
were discovered in Dubna**

Questions and answers:

- ✓ Do the superheavy elements exist? – **YES!**
- ✓ Does the “Island of stability” of superheavy elements exist? – **YES!**
- ✓ How superheavy elements can be synthesized? – **fusion of ^{48}Ca with Actinides works**
- ? How many new elements can be synthesized in the nearest future – **119?, 120?, ???**
How many they are?
- ? What are the properties (atomic, nuclear) of already known SHE?
- ? How to reach the center of the Island of stability? – **???**
- ? How long do the most stable nuclei from the Island of stability live - **???**
- ? Can superheavy elements be produced in nature? - **???**

Superheavy Element Factory



Superheavy Element Factory



Cyclotron DC-280:

- **Dec., 26 2018:** first beam was obtained;
- **Jan.-June 2019:** design parameters are nearly reached.
designed: beam intensity – 10 μA with 50% efficiency

Gas-filled recoil separator (GFRS-2):

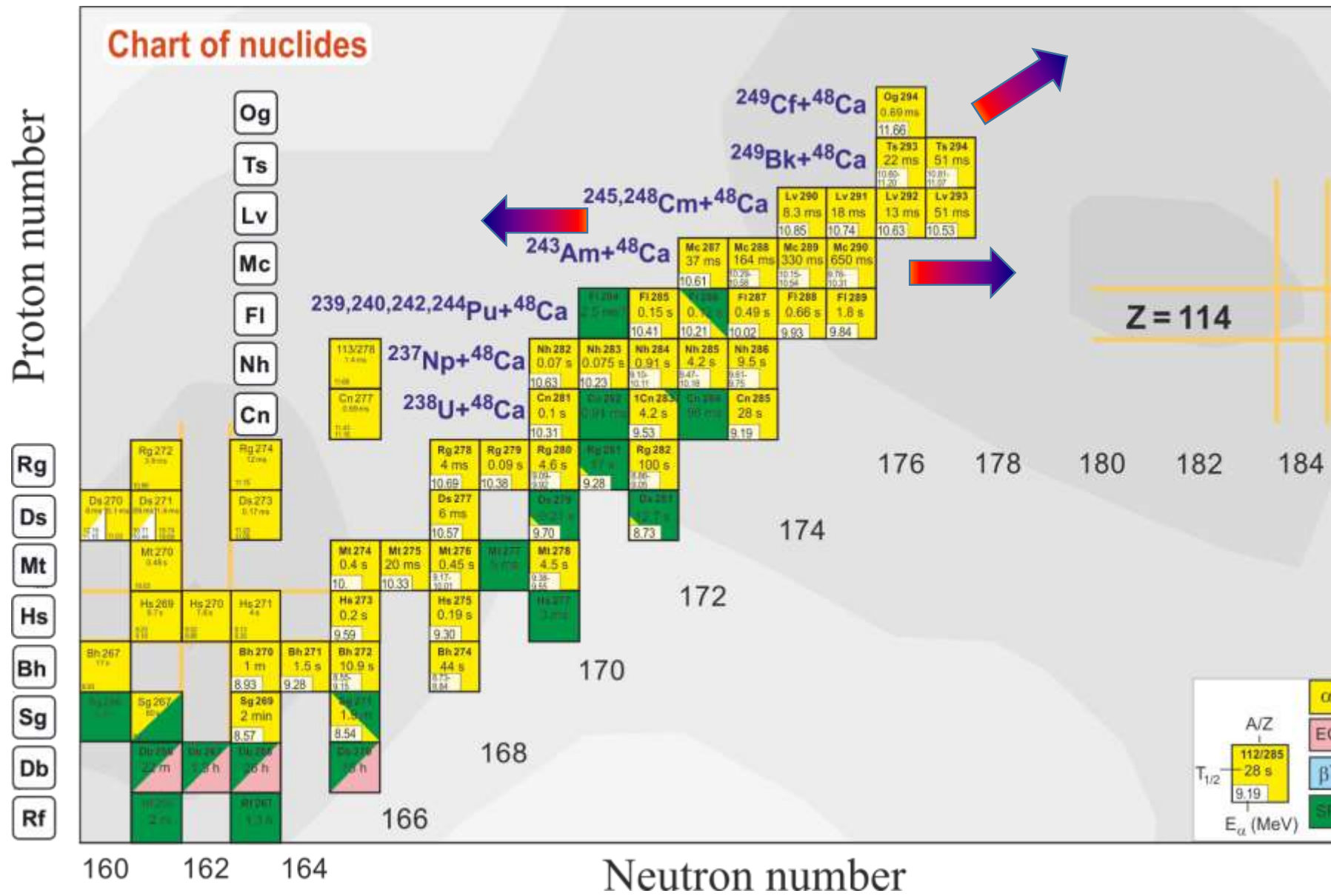
- under commissioning

plans for the end of 2019:

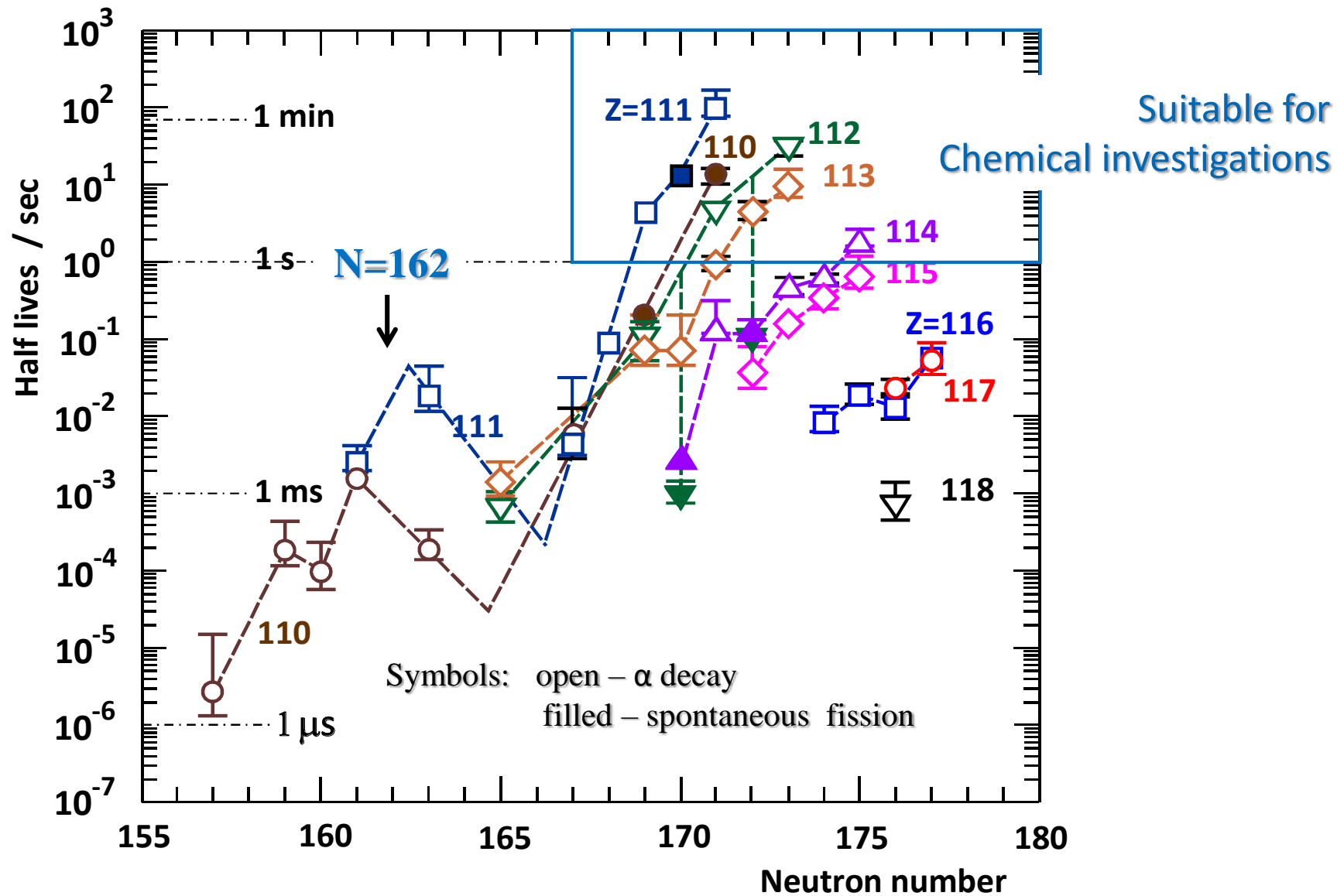
- **now:** separator testing and tuning;
- **next:** First experiment $^{48}\text{Ca} + ^{243}\text{Am}$;
- Preparing the experiment aimed at synthesis of element **120** in the $^{50}\text{Ti} + ^{249-251}\text{Cf}$ reaction;



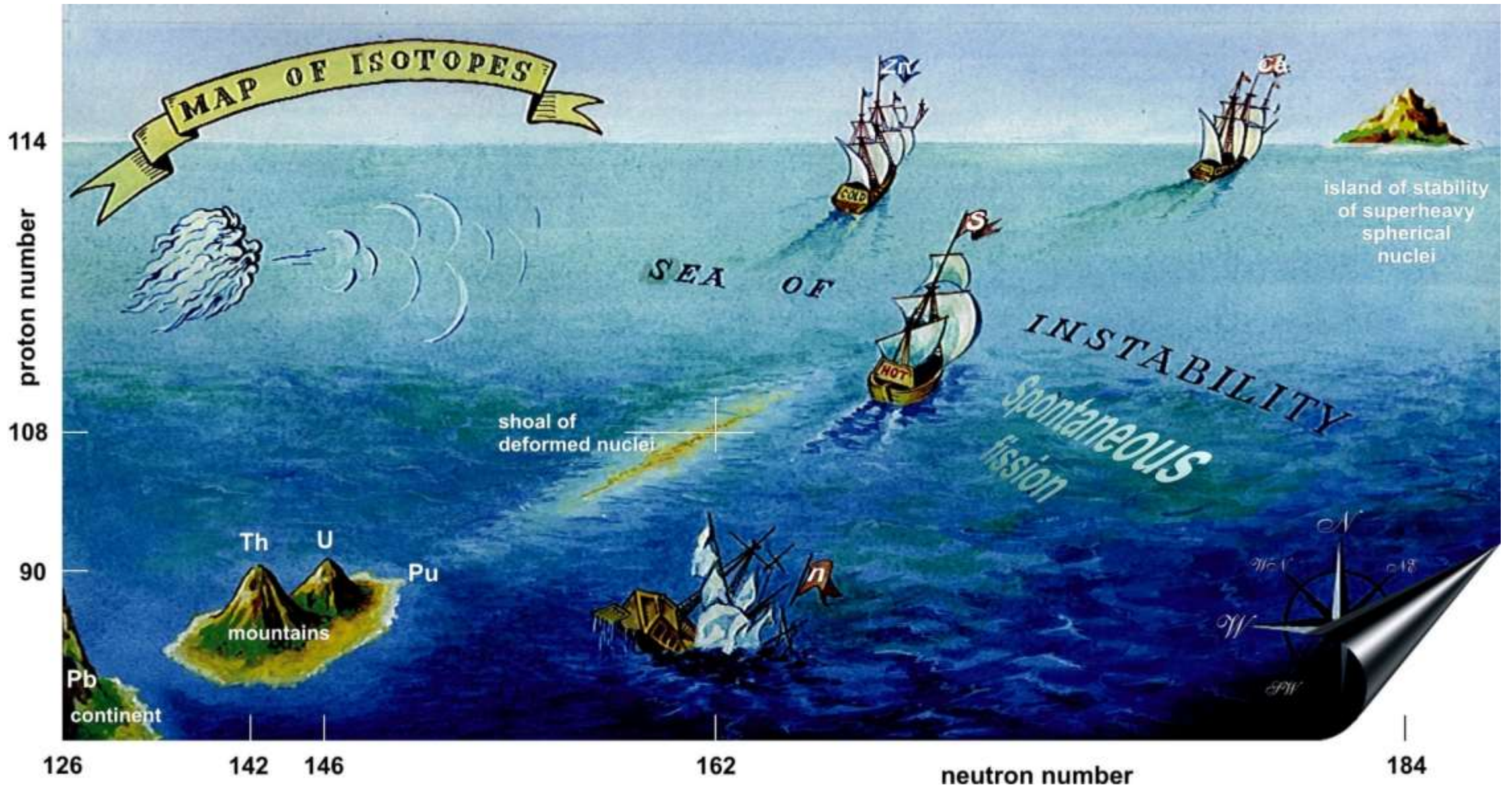
Fusion reactions: *left, right or up?*



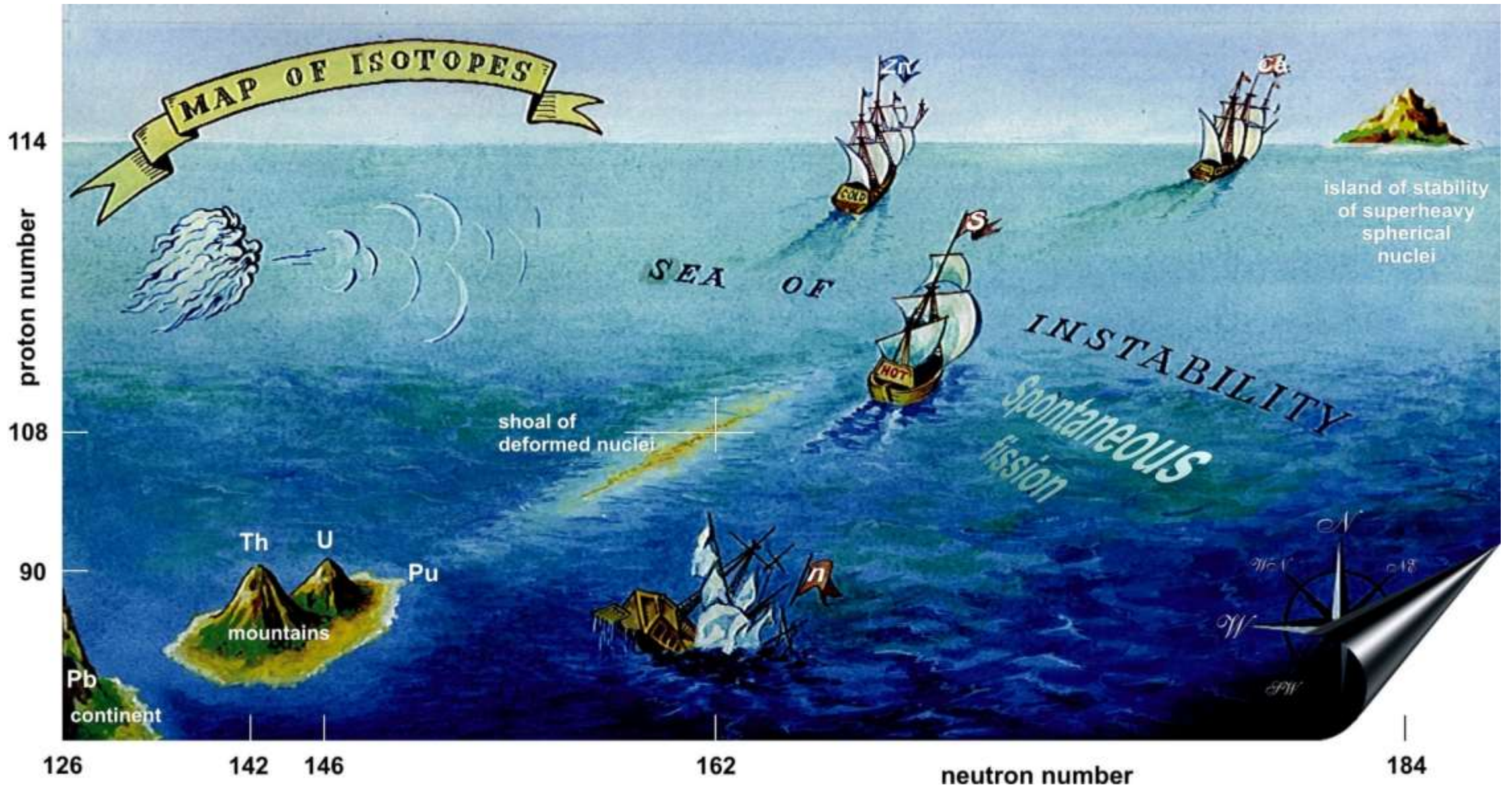
Half-lives of nuclides with $Z \geq 110$



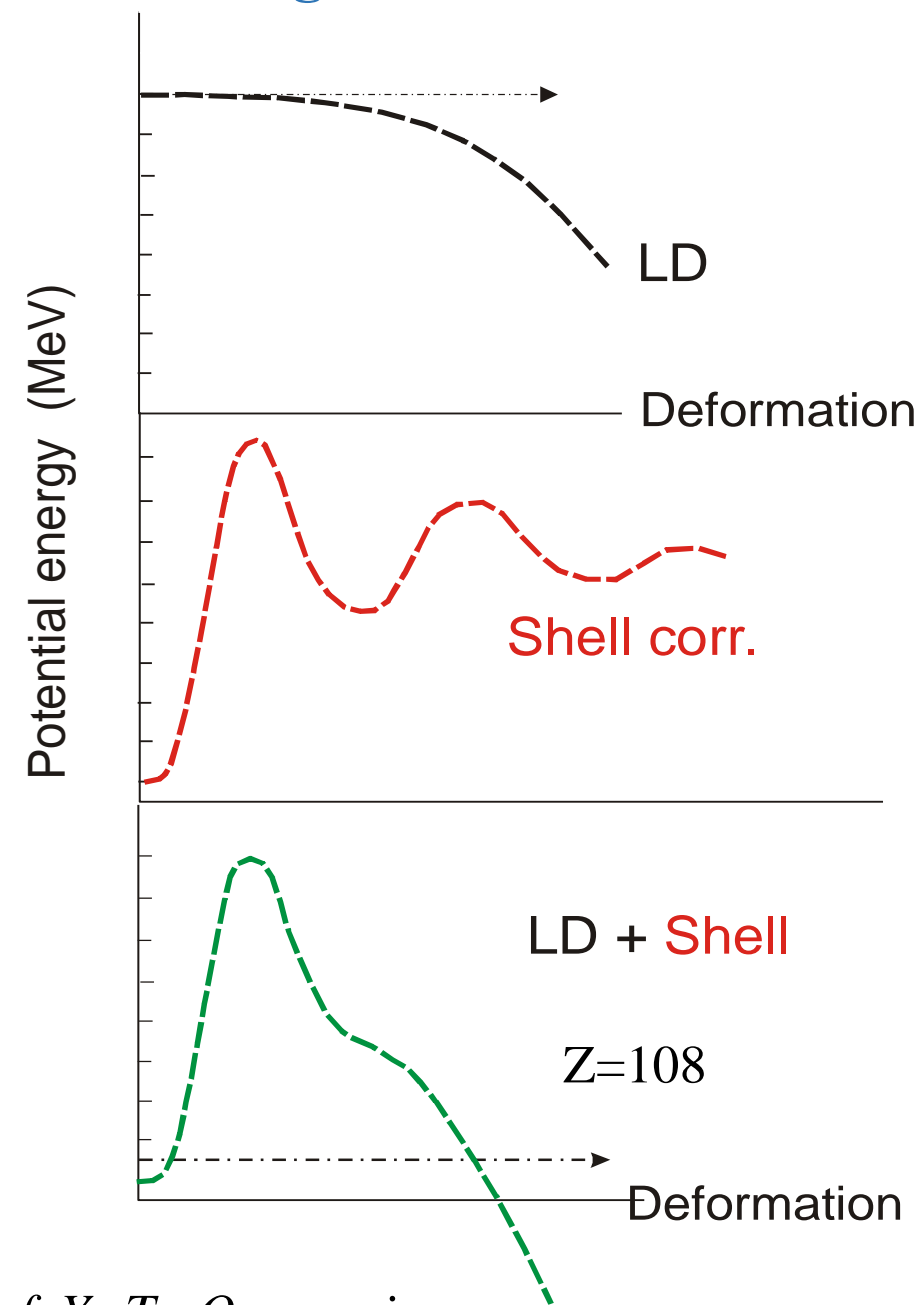
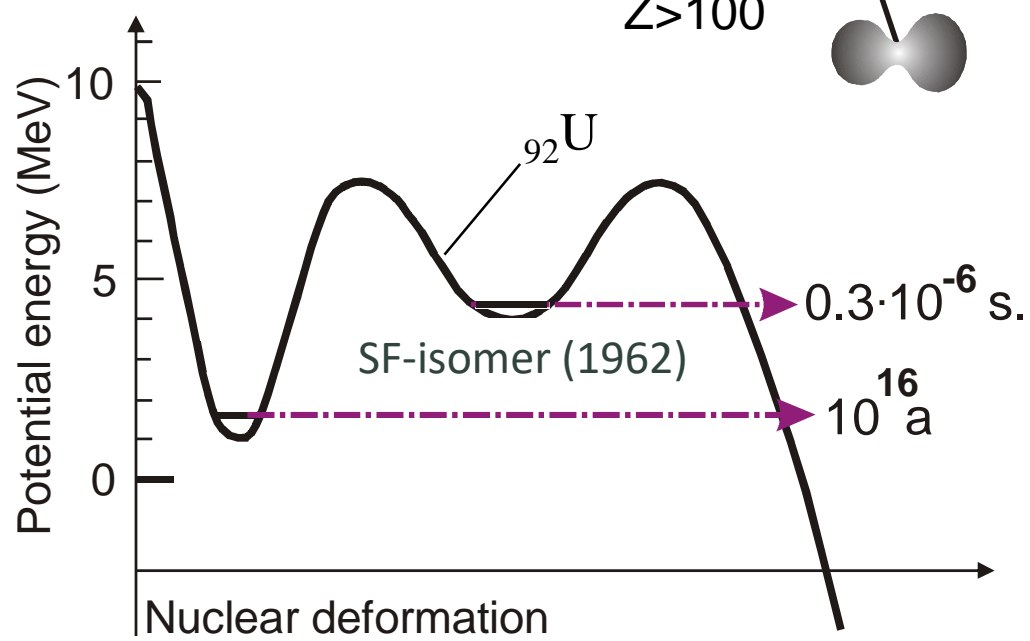
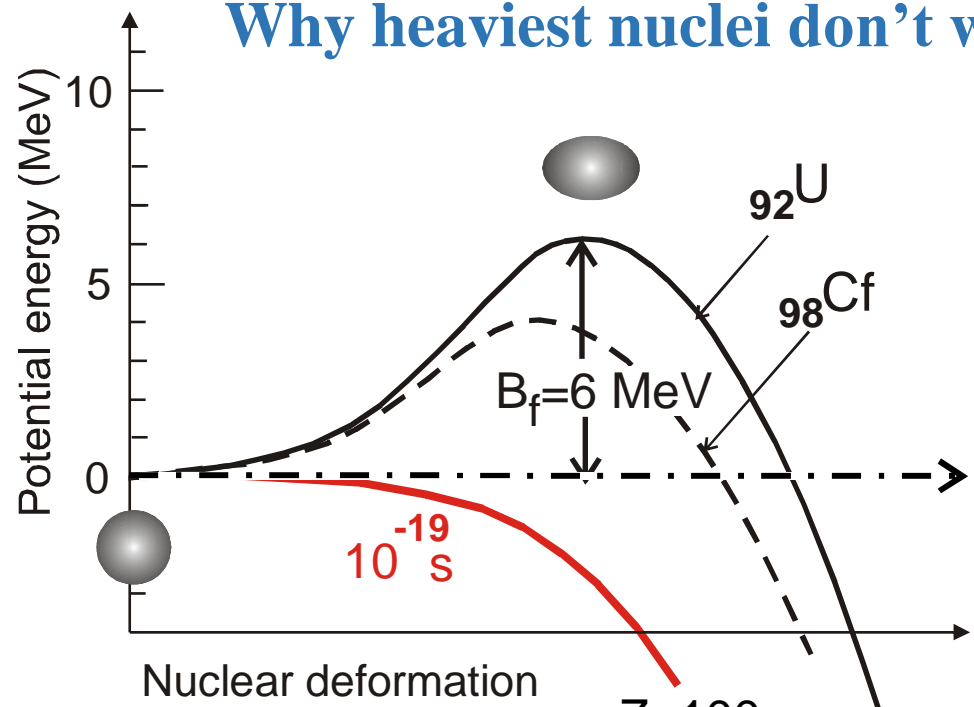
Long way to new Lands



Long way to new Lands



Why heaviest nuclei don't want to live long?



Courtesy: Prof. Yu.Ts. Oganessian