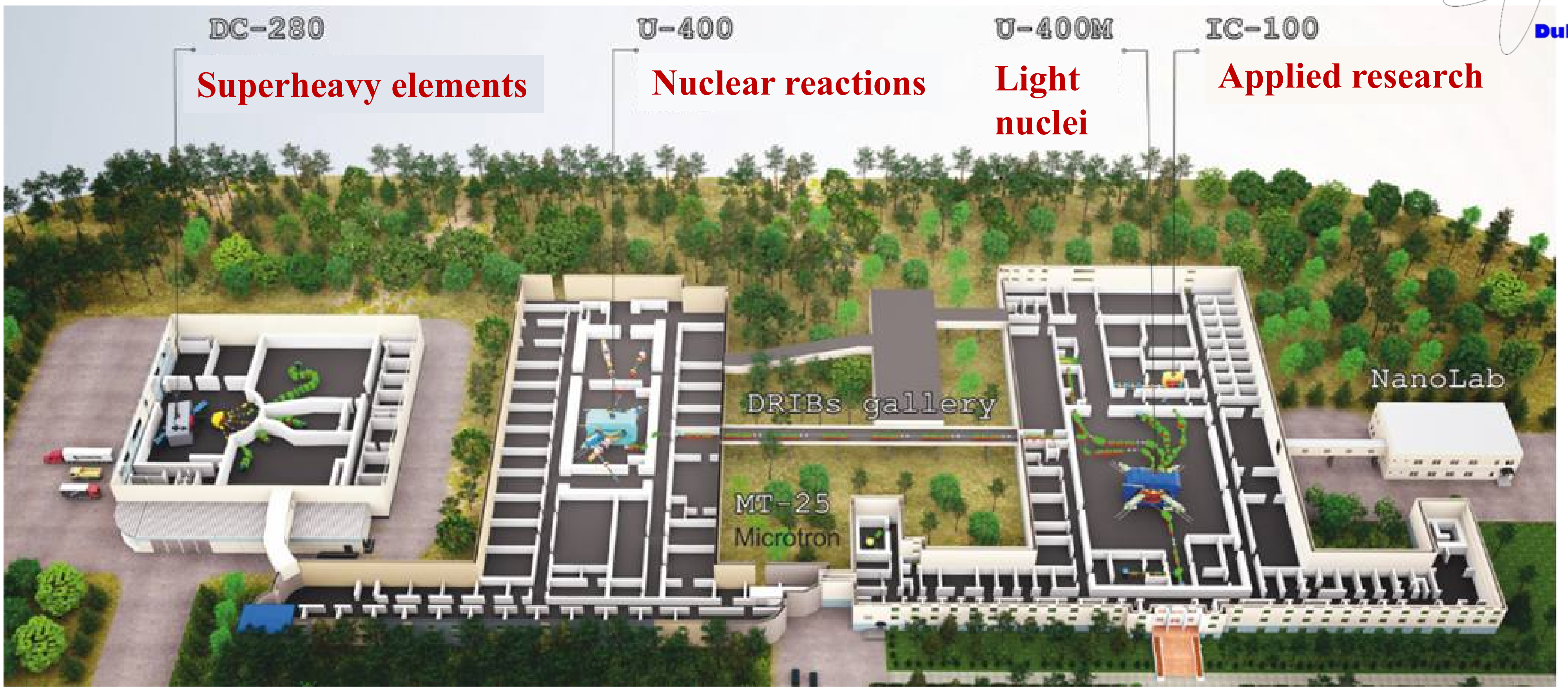
Flerov Laboratory of Nuclear Reactions

Alexander Karpov (*karpov@jinr.ru*)

FLNR, JINR

DRIBS-III ACCELERATOR COMPLEX

FLEROV LABORATORY OF NUCLEAR REACTIONS



FLNR's basic directions of research:

- Heavy and superheavy nuclei
- Light exotic nuclei
- Radiation effects and physical groundwork of nanotechnology
- Accelerator technologies

Superheavy elements: synthesis and properties

Study of heavy and superheavy elements in the world

1 **Berkeley National Laboratory, USA**

2 **GANIL, Caen, France**

3 **Helmholtz Centre GSI, Darmstadt, Germany**

4 **JINR, Dubna, Russia**

5 **IMP, Lanzhou, China**

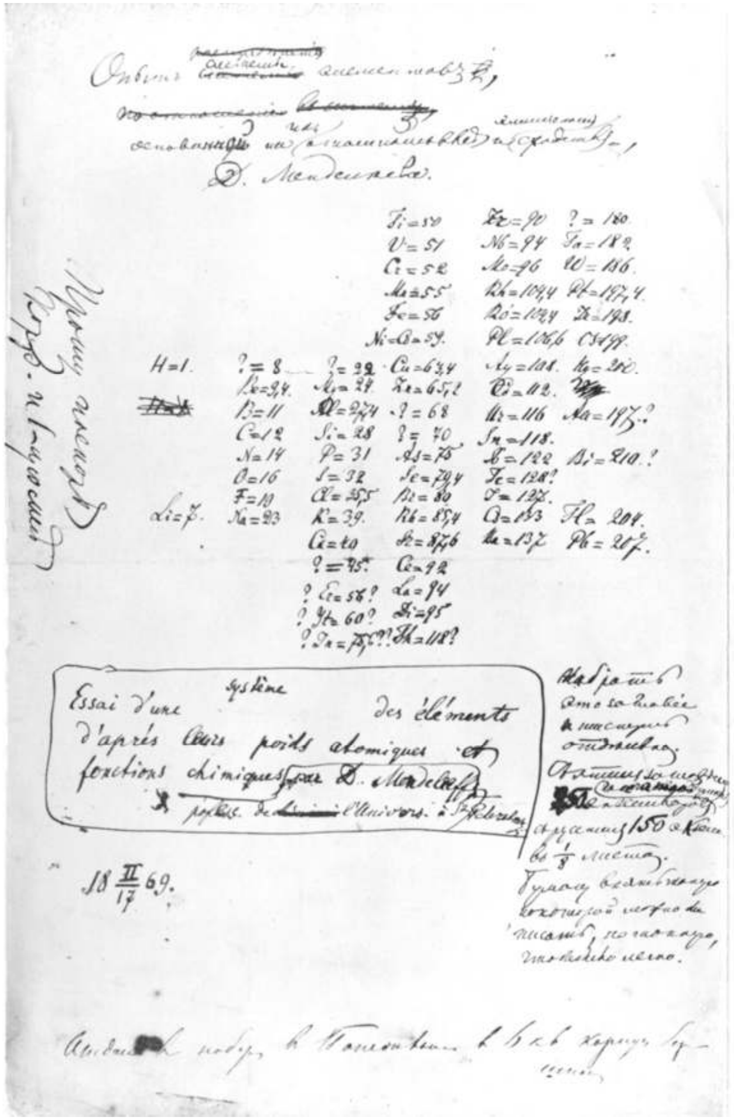
6 **RIKEN, Wako, Japan**

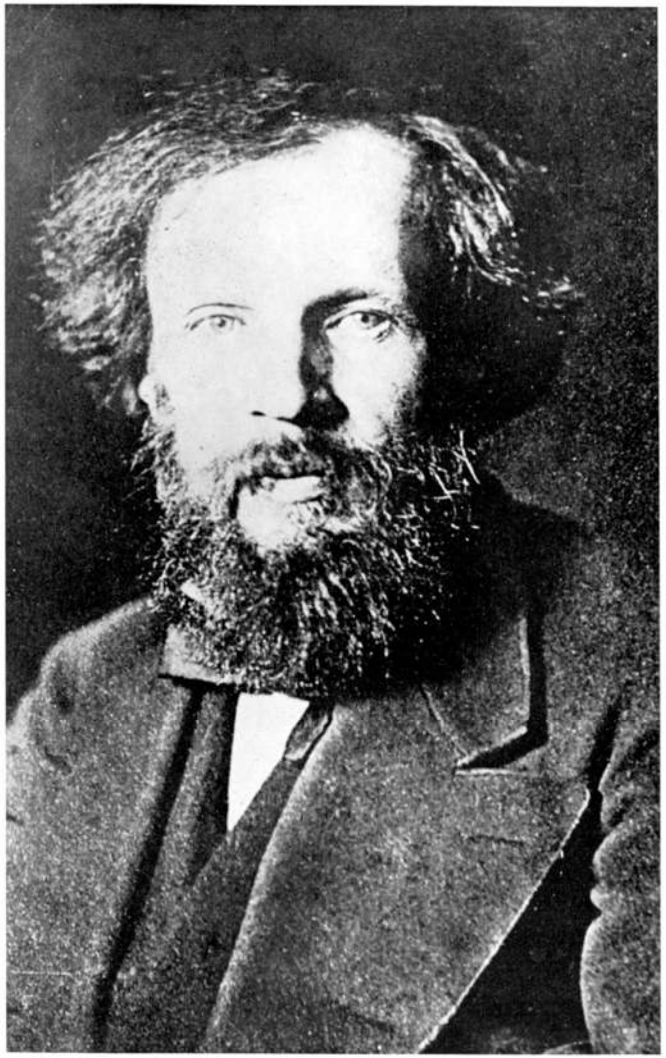
Advantages of JINR:

- wide range of accelerated ions;
- availability of actinide isotopes for targets;
- broad international cooperation (JINR Member States; Livermore & Oak Ridge National Laboratories, Vanderbilt University, University of Tennessee, USA; Paul Scherer Institute, Switzerland, University Louis Pasteur, University Paris Sud, GANIL, France; IMP, Lanzhou, China);
- longstanding traditions and a scientific school;
- full-time availability of an accelerator complex – SHE-Factory.

Mendeleev Periodic Table of Chemical Elements (1869)

2019 International Year of the Periodic Table of Chemical Elements


Essai d'une système des éléments d'après leurs poids atomiques et fonctions chimiques par D. Mendeleeff



Periodic Table today (since November, 28, 2016)

Key: atomic number / **Symbol** / name / abridged standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.0080 ±0.0002																	2 **He** helium 4.0026 ±0.0001
3 **Li** lithium 6.94 ±0.06	4 **Be** beryllium 9.0122 ±0.0001											5 **B** boron 10.81 ±0.02	6 **C** carbon 12.011 ±0.002	7 **N** nitrogen 14.007 ±0.001	8 **O** oxygen 15.999 ±0.001	9 **F** fluorine 18.998 ±0.001	10 **Ne** neon 20.180 ±0.001
11 **Na** sodium 22.990 ±0.001	12 **Mg** magnesium 24.305 ±0.002											13 **Al** aluminium 26.982 ±0.001	14 **Si** silicon 28.085 ±0.001	15 **P** phosphorus 30.974 ±0.001	16 **S** sulfur 32.06 ±0.02	17 **Cl** chlorine 35.45 ±0.01	18 **Ar** argon 39.95 ±0.16
19 **K** potassium 39.098 ±0.001	20 **Ca** calcium 40.078 ±0.004	21 **Sc** scandium 44.956 ±0.001	22 **Ti** titanium 47.867 ±0.001	23 **V** vanadium 50.942 ±0.001	24 **Cr** chromium 51.996 ±0.001	25 **Mn** manganese 54.938 ±0.001	26 **Fe** iron 55.845 ±0.002	27 **Co** cobalt 58.933 ±0.001	28 **Ni** nickel 58.693 ±0.001	29 **Cu** copper 63.546 ±0.003	30 **Zn** zinc 65.38 ±0.02	31 **Ga** gallium 69.723 ±0.001	32 **Ge** germanium 72.630 ±0.008	33 **As** arsenic 74.922 ±0.001	34 **Se** selenium 78.971 ±0.008	35 **Br** bromine 79.904 ±0.003	36 **Kr** krypton 83.798 ±0.002
37 **Rb** rubidium 85.468 ±0.001	38 **Sr** strontium 87.62 ±0.01	39 **Y** yttrium 88.906 ±0.001	40 **Zr** zirconium 91.224 ±0.002	41 **Nb** niobium 92.906 ±0.001	42 **Mo** molybdenum 95.95 ±0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ±0.02	45 **Rh** rhodium 102.91 ±0.01	46 **Pd** palladium 106.42 ±0.01	47 **Ag** silver 107.87 ±0.01	48 **Cd** cadmium 112.41 ±0.01	49 **In** indium 114.82 ±0.01	50 **Sn** tin 118.71 ±0.01	51 **Sb** antimony 121.76 ±0.01	52 **Te** tellurium 127.60 ±0.03	53 **I** iodine 126.90 ±0.01	54 **Xe** xenon 131.29 ±0.01
55 **Cs** caesium 132.91 ±0.01	56 **Ba** barium 137.33 ±0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ±0.01	73 **Ta** tantalum 180.95 ±0.01	74 **W** tungsten 183.84 ±0.01	75 **Re** rhenium 186.21 ±0.01	76 **Os** osmium 190.23 ±0.03	77 **Ir** iridium 192.22 ±0.01	78 **Pt** platinum 195.08 ±0.02	79 **Au** gold 196.97 ±0.01	80 **Hg** mercury 200.59 ±0.01	81 **Tl** thallium 204.38 ±0.01	82 **Pb** lead 207.2 ±1.1	83 **Bi** bismuth 208.98 ±0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	104 **Rf** rutherfordium [267]	105 **Db** dubnium [268]	106 **Sg** seaborgium [269]	107 **Bh** bohrium [270]	108 **Hs** hassium [269]	109 **Mt** meitnerium [277]	110 **Ds** darmstadtium [281]	111 **Rg** roentgenium [282]	112 **Cn** copernicium [285]	113 **Nh** nihonium [286]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

57 **La** lanthanum 138.91 ±0.01	58 **Ce** cerium 140.12 ±0.01	59 **Pr** praseodymium 140.91 ±0.01	60 **Nd** neodymium 144.24 ±0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ±0.02	63 **Eu** europium 151.96 ±0.01	64 **Gd** gadolinium 157.25 ±0.03	65 **Tb** terbium 158.93 ±0.01	66 **Dy** dysprosium 162.50 ±0.01	67 **Ho** holmium 164.93 ±0.01	68 **Er** erbium 167.26 ±0.01	69 **Tm** thulium 168.93 ±0.01	70 **Yb** ytterbium 173.05 ±0.02	71 **Lu** lutetium 174.97 ±0.01
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ±0.01	91 **Pa** protactinium 231.04 ±0.01	92 **U** uranium 238.03 ±0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

Abundance of Elements in the Universe

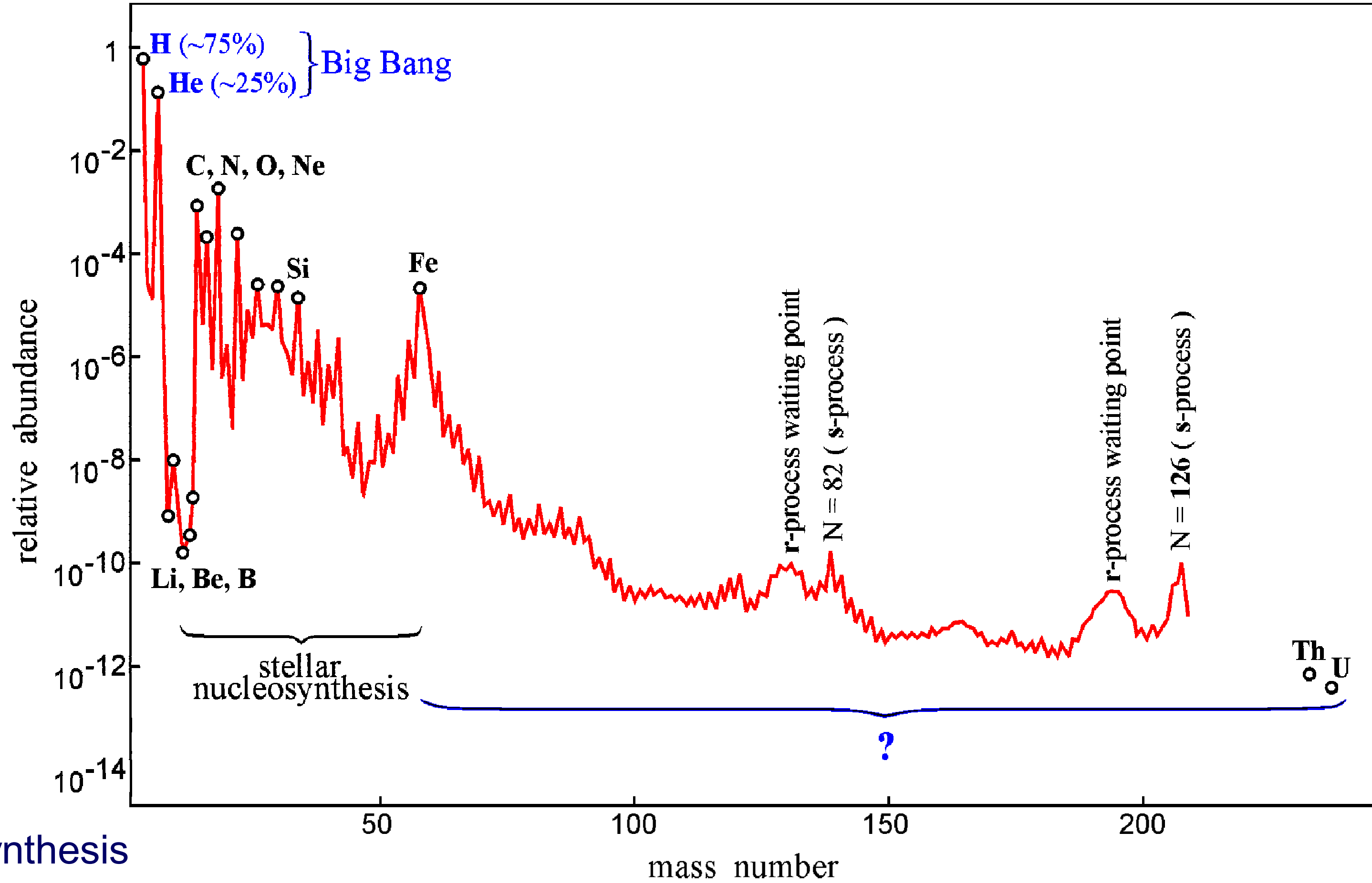
The 11 Greatest Unanswered Questions of Physics
(National Research Council, NAS, USA, 2002):

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:

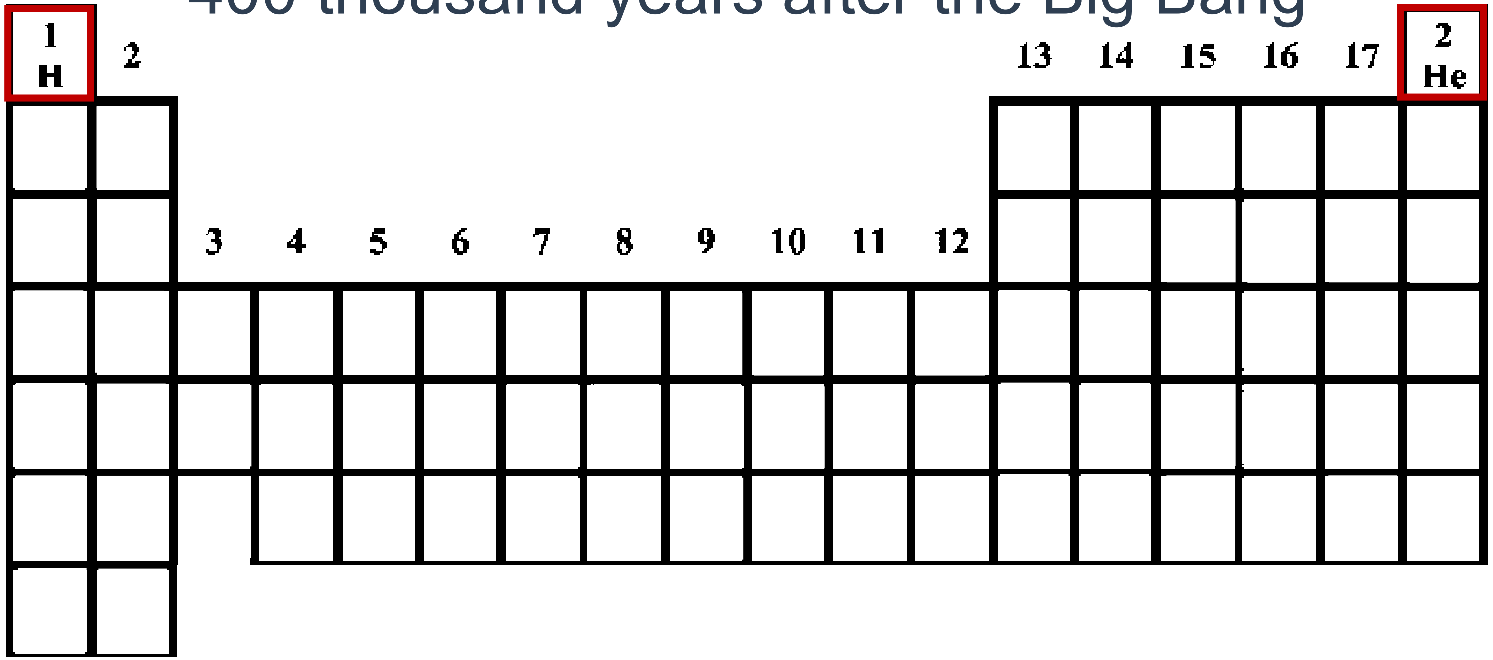
Discovery of gravitational waves →
first observation of gravitational waves in a neutron star merge →
start of multimessage astronomy



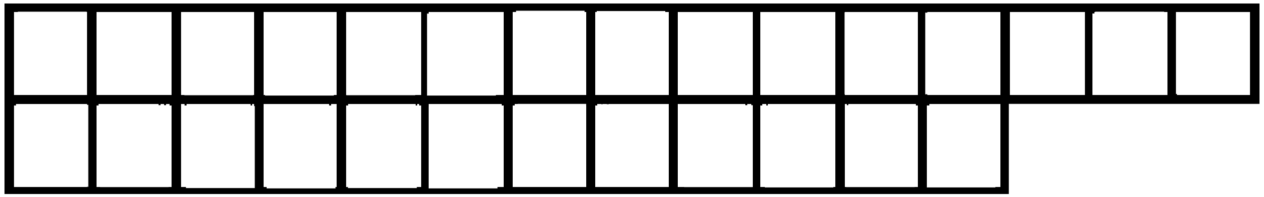
future
understanding of astrophysical nucleosynthesis

D.I. Mendeleev Periodic Table

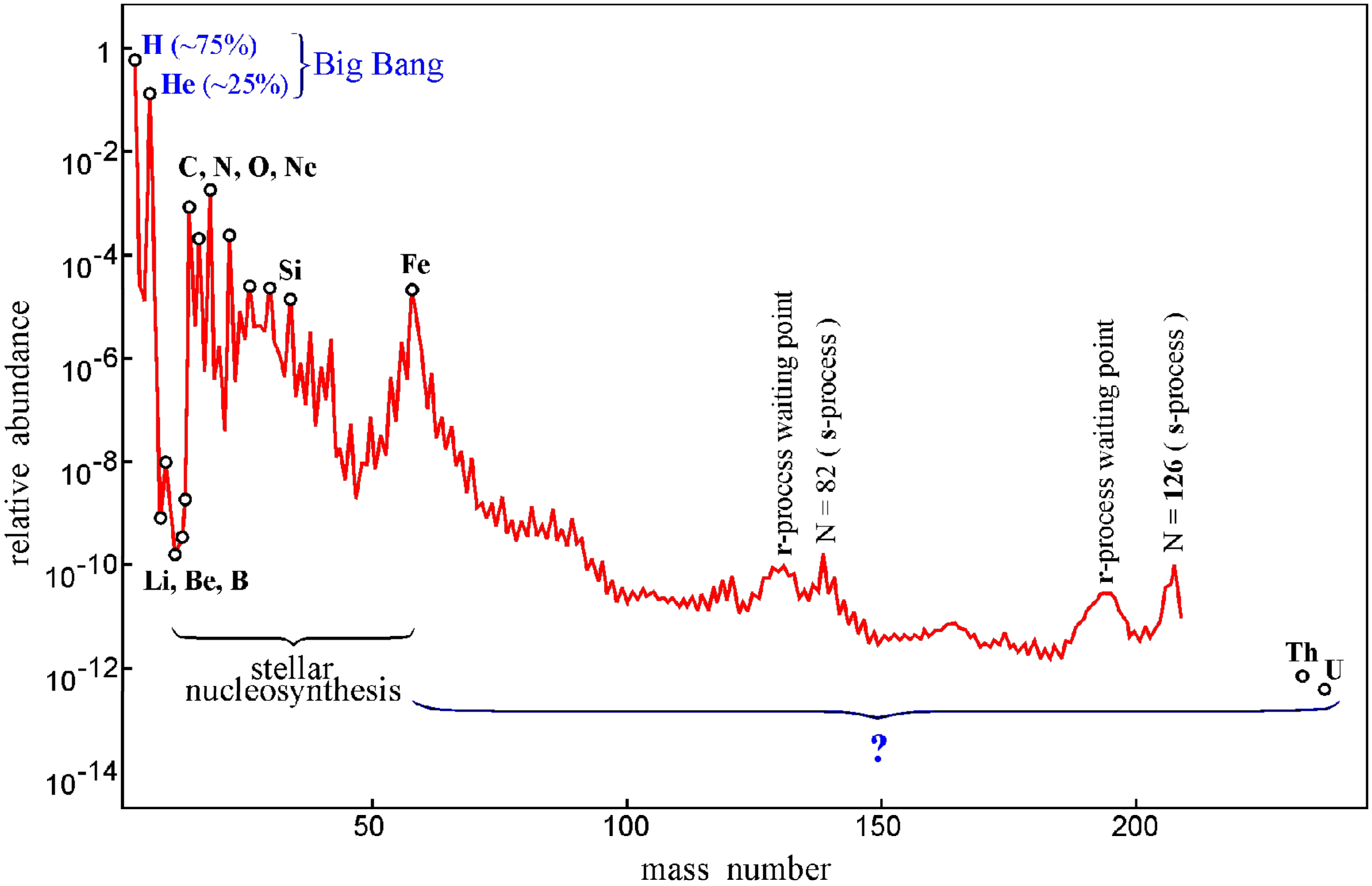
~400 thousand years after the Big Bang



At present, our Universe still consists on almost 100% of Hydrogen and Helium

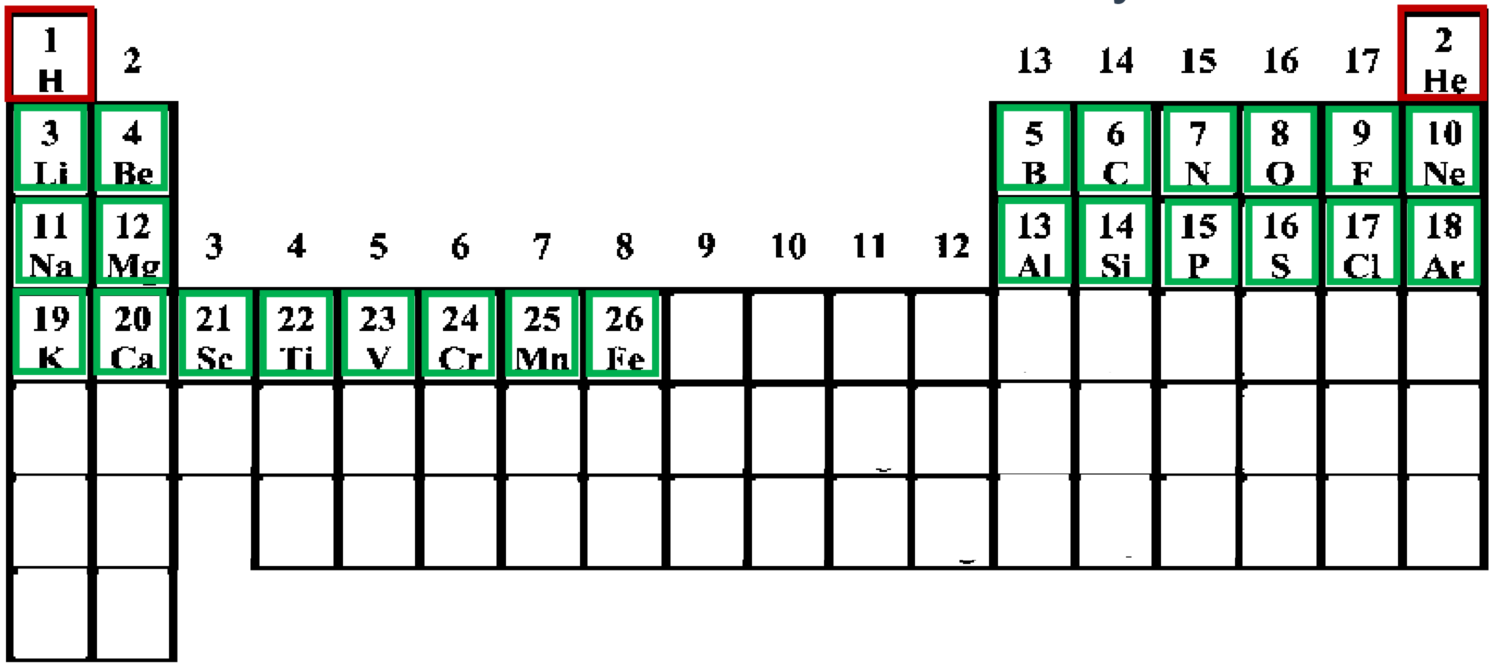


Abundance of Elements in the Universe

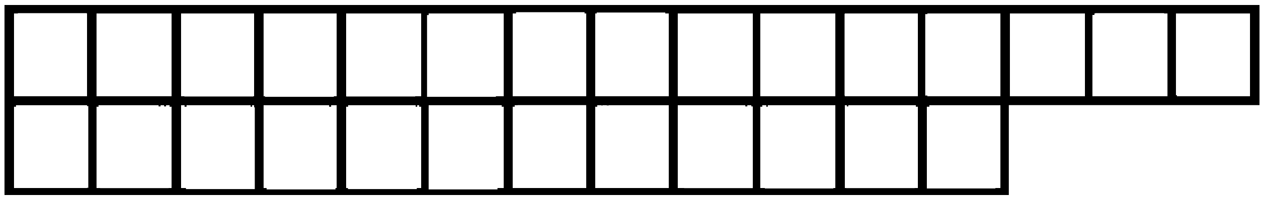


D.I. Mendeleev Periodic Table

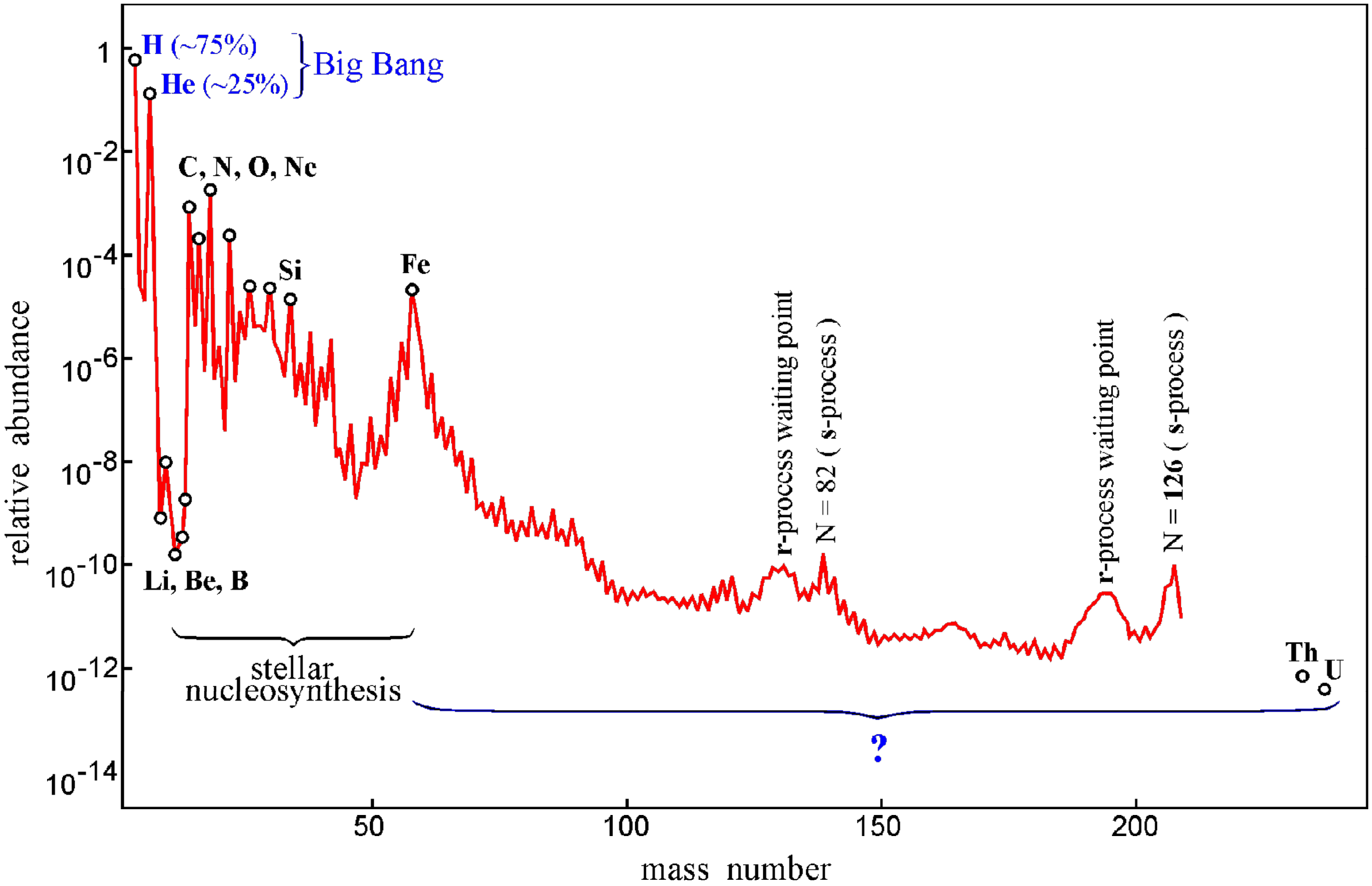
in the end of massive stars stationary evolution



What is the origin of elements heavier than iron?



Abundance of Elements in the Universe



D.I. Mendeleev Periodic Table

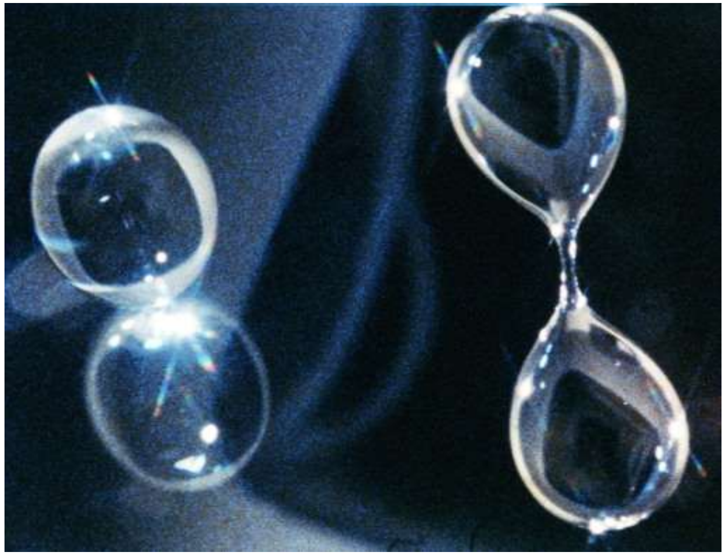
when neutrons start acting

1 H	2											13	14	15	16	17	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																

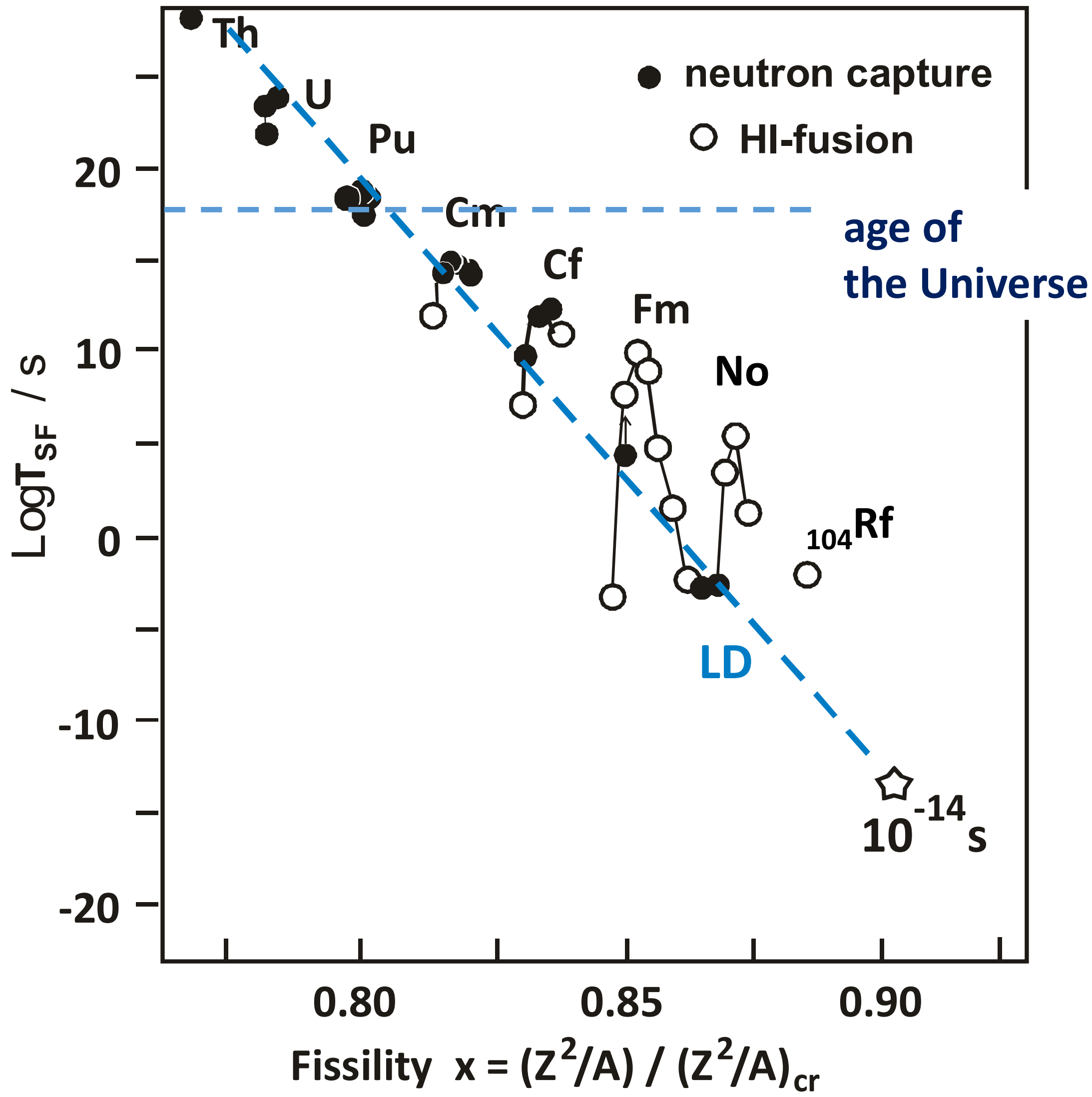
Are there still heavier elements?

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U											

Spontaneous fission limits existence of chemical elements

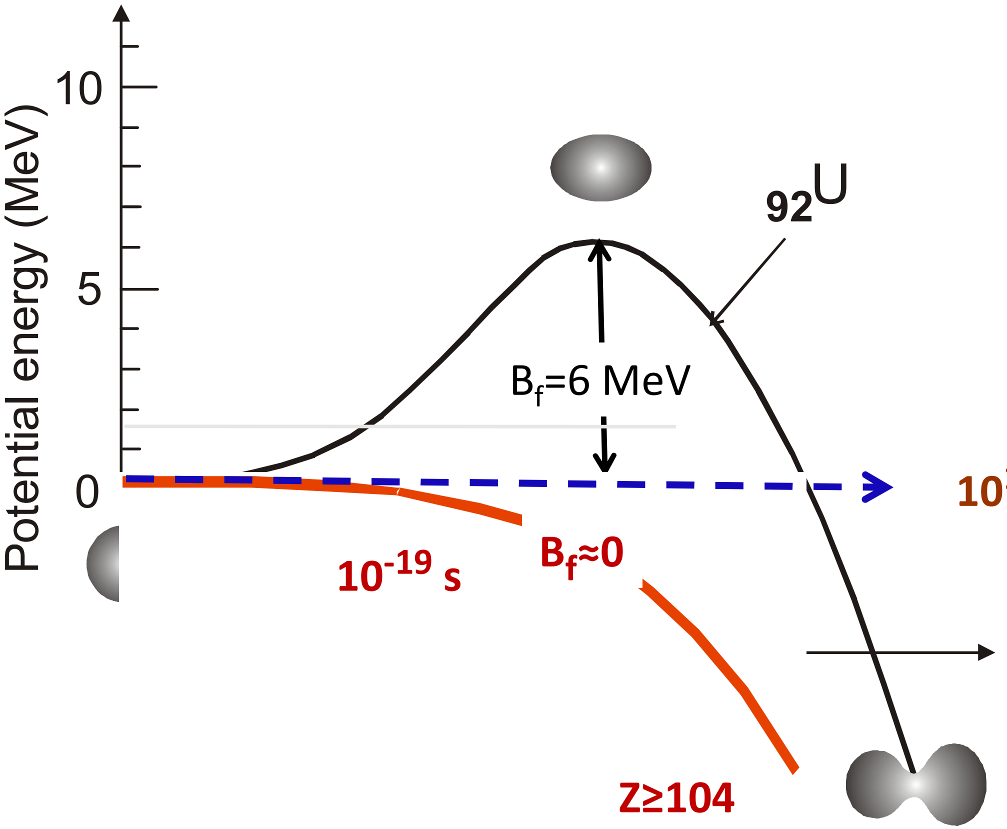


Drop of water in microgravity (NASA, 2005)



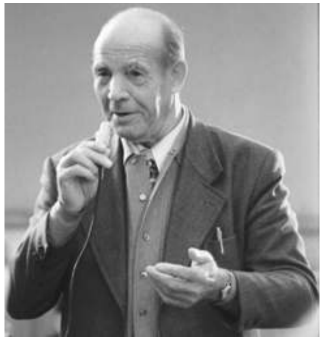
1939
Nuclear fission
(theory)

N. Bohr   J.A. Wheeler



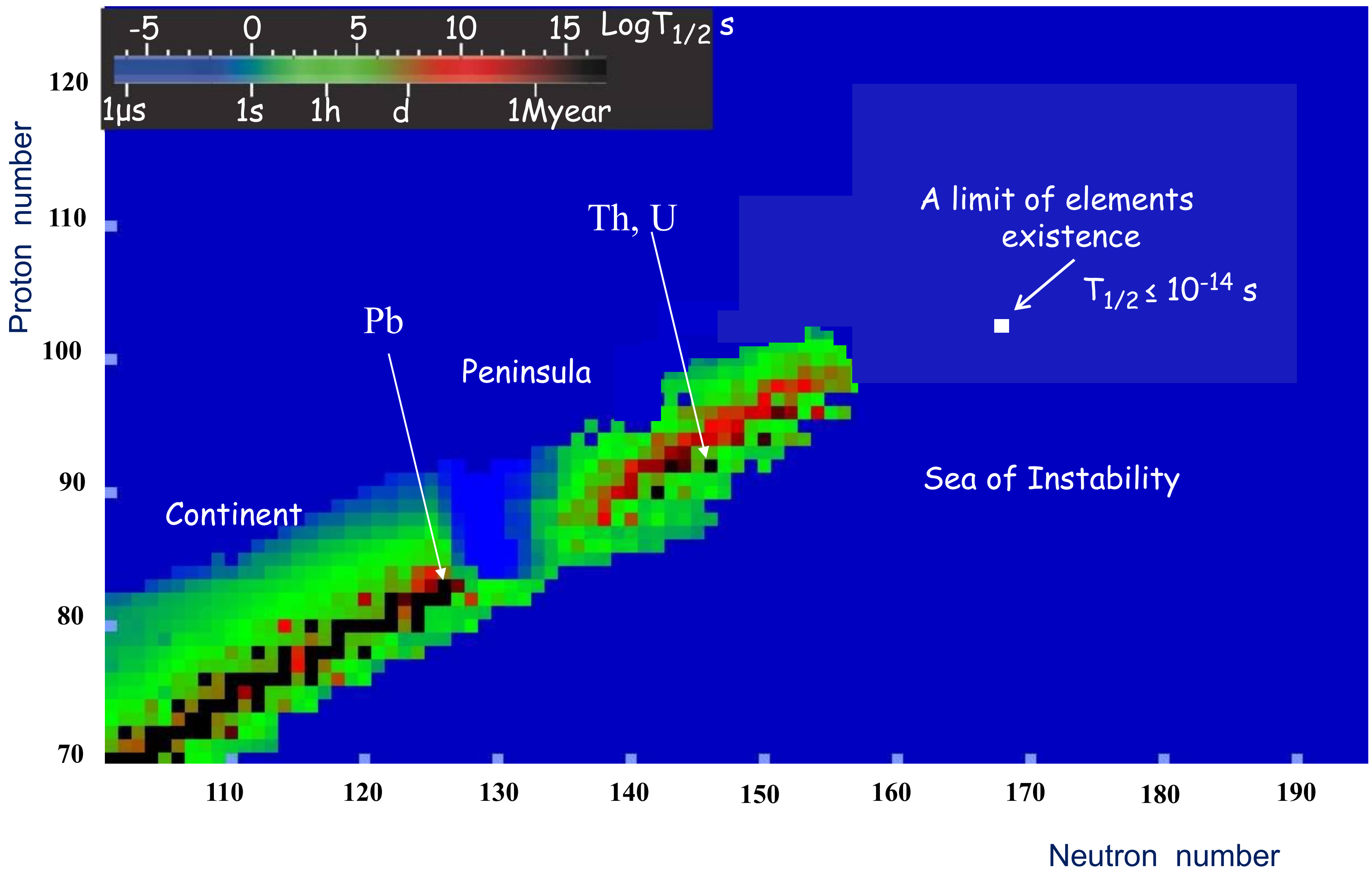
G.N. Flerov

1940
Nuclear fission
(radioactivity)



K.A. Petrzhak

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



Spontaneous fission half-lives with microscopic (shell) effects

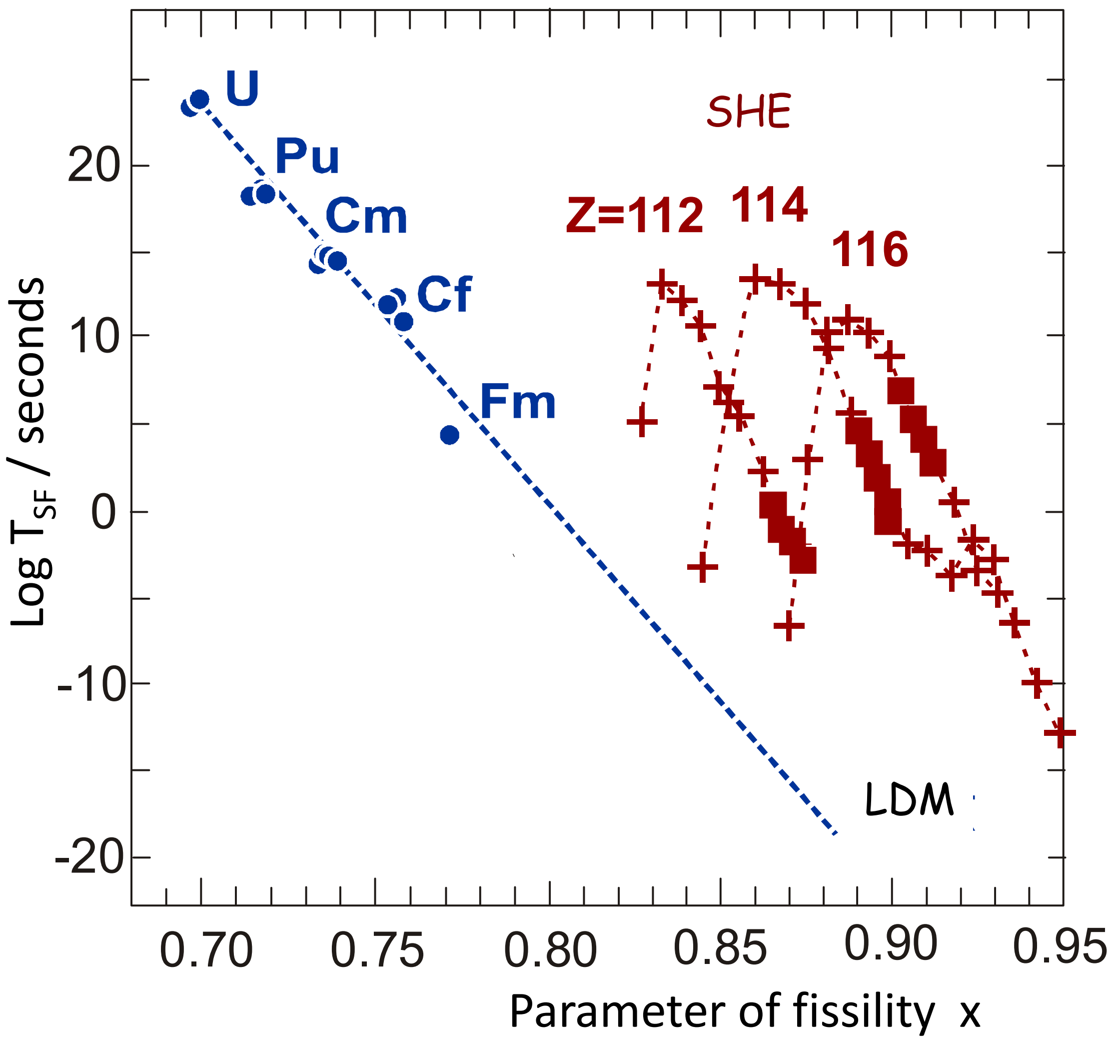
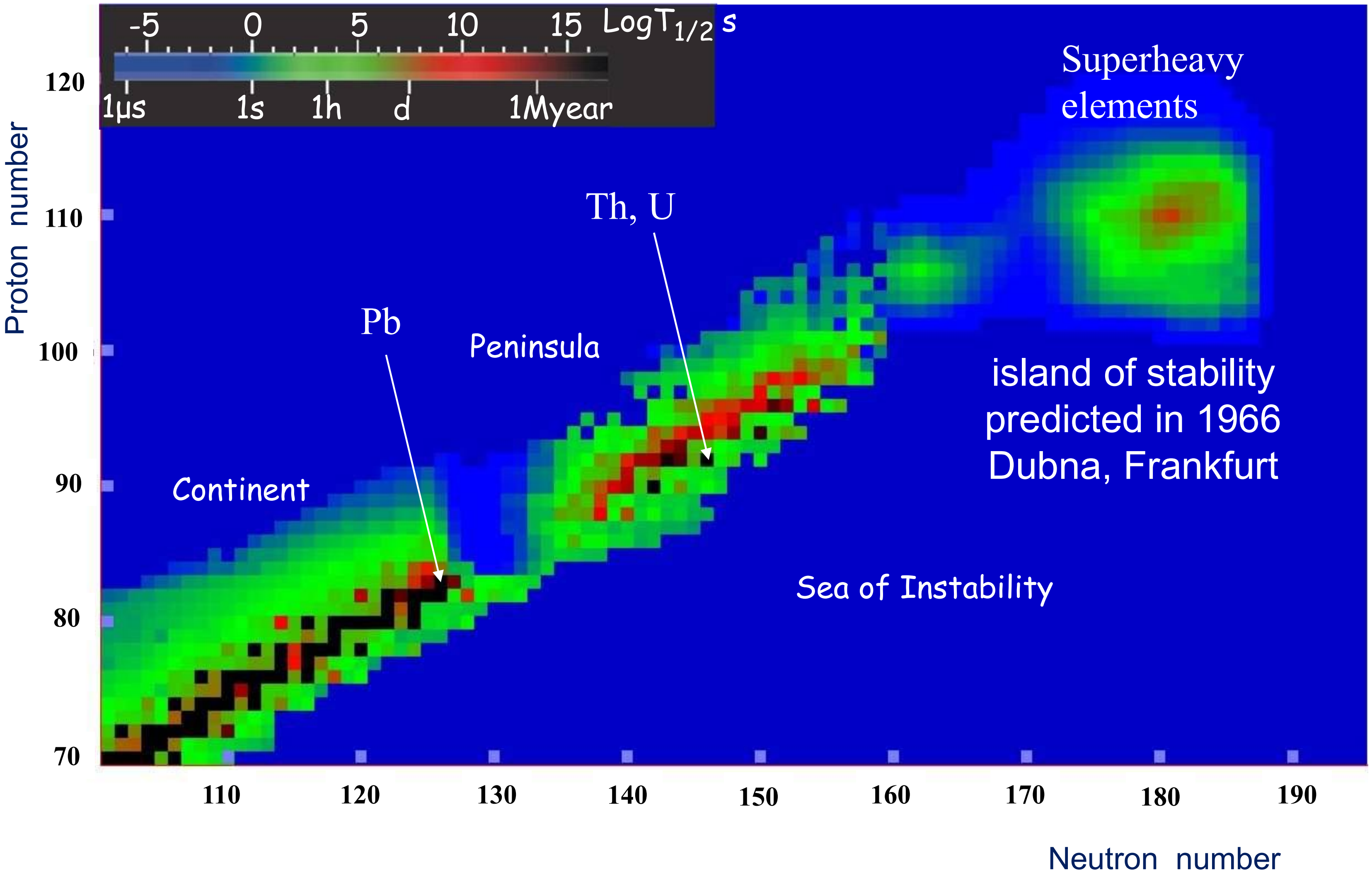
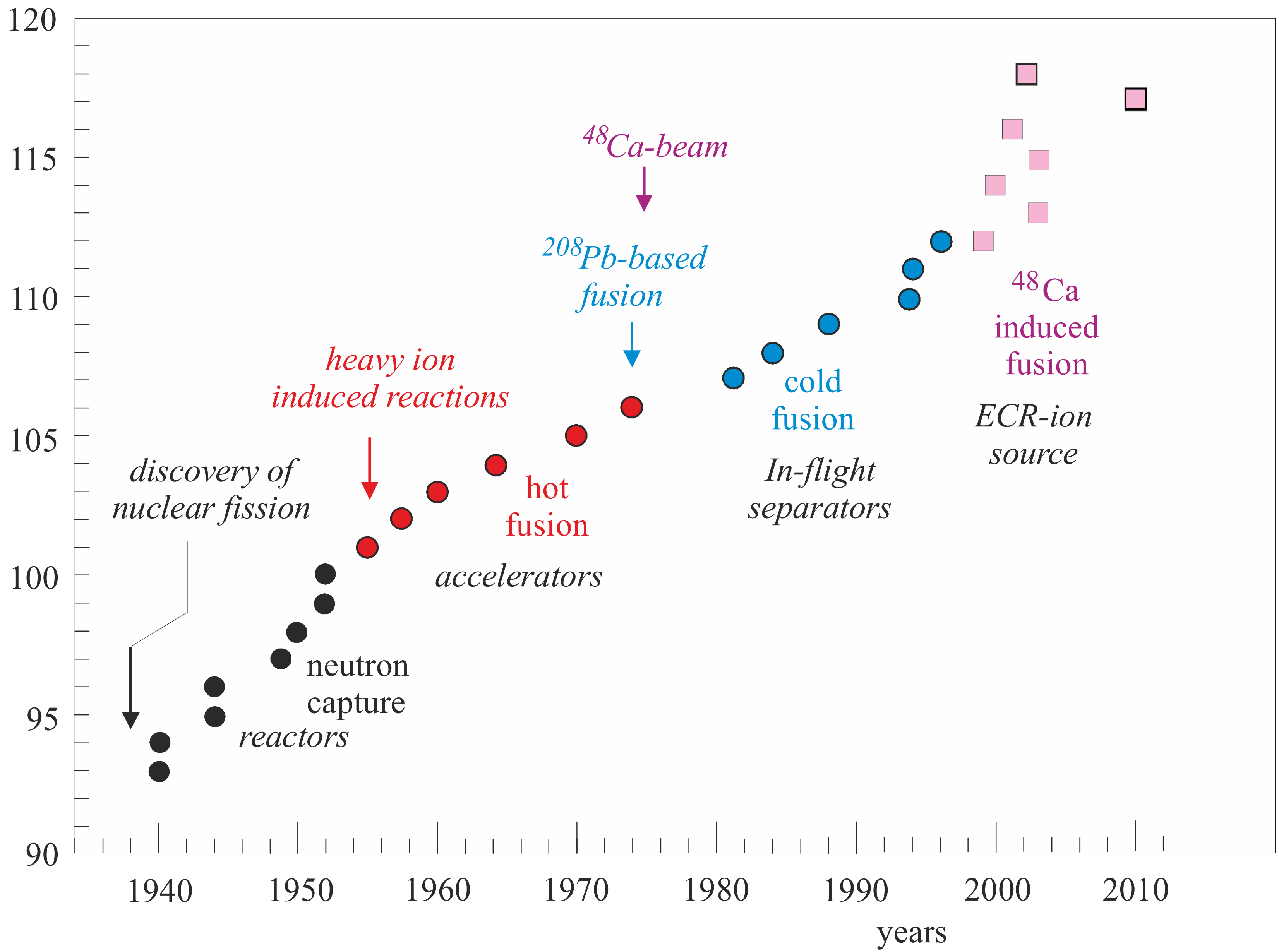
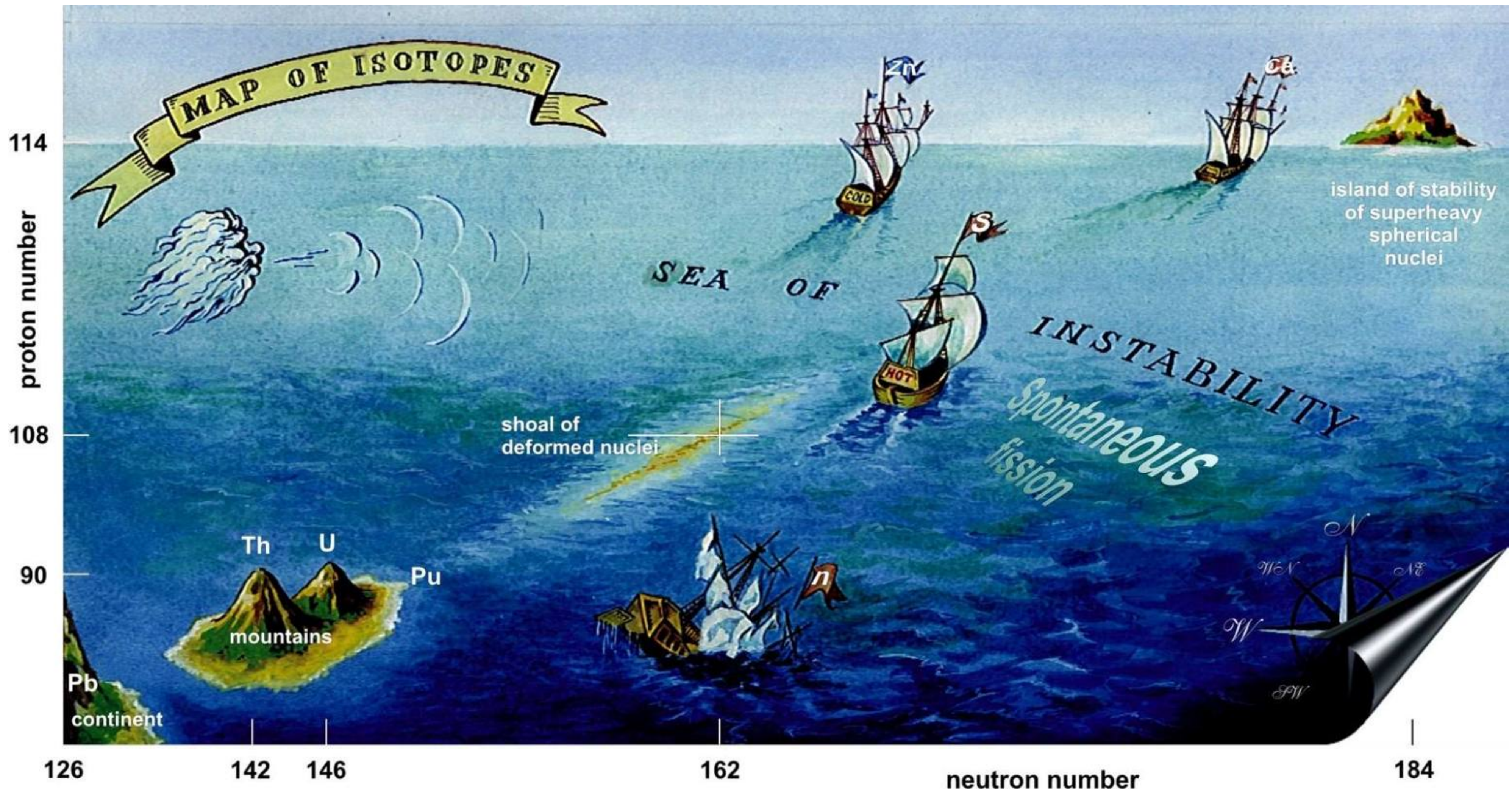


Chart of nuclei (upper part)



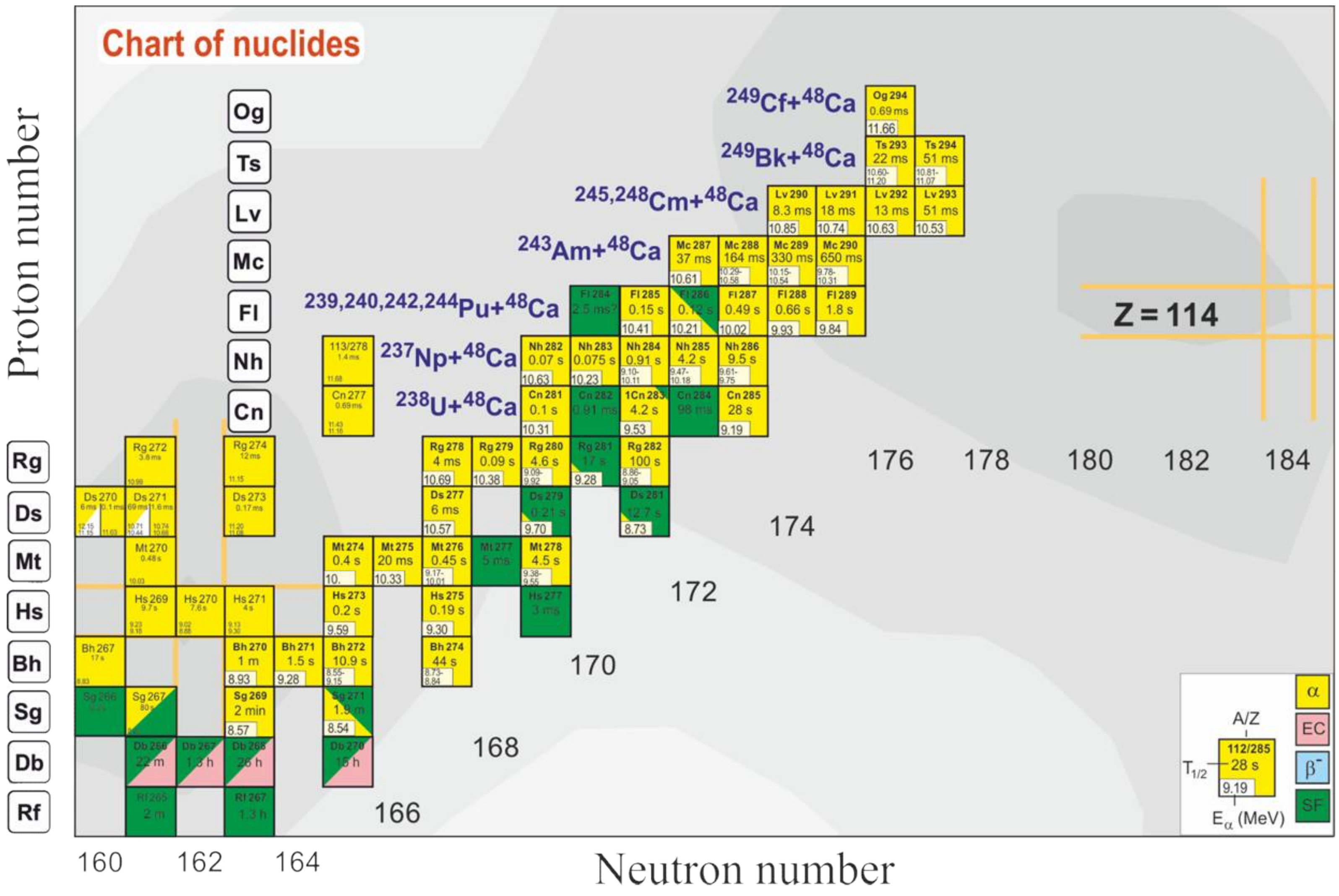


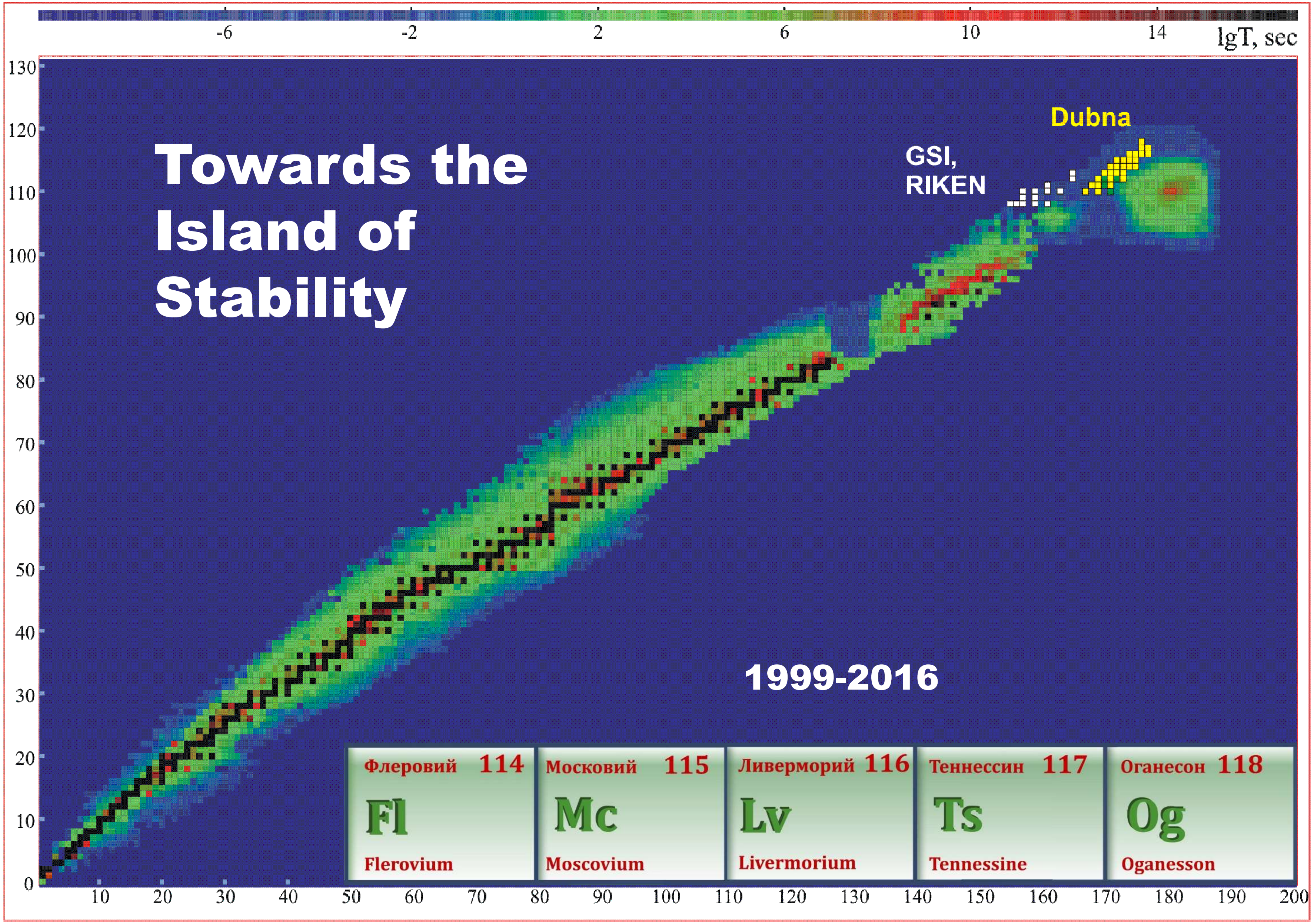
120
115
110
105
100
95
90
1940
1950
1960
1970
1980
1990
2000
2010
years
48Ca-beam
208Pb-based fusion
heavy ion induced reactions
discovery of nuclear fission
neutron capture
reactors
hot fusion
accelerators
cold fusion
In-flight separators
48Ca induced fusion
ECR-ion source



MAP OF ISOTOPES
SEA OF INSTABILITY
Spontaneous fission
island of stability of superheavy spherical nuclei
shoal of deformed nuclei
COLD
HOT
S
n
Th
U
Pu
mountains
Pb
continent
114
108
90
proton number
126
142
146
162
184
neutron number

Synthesis of Superheavy Nuclei (*since 1999*)





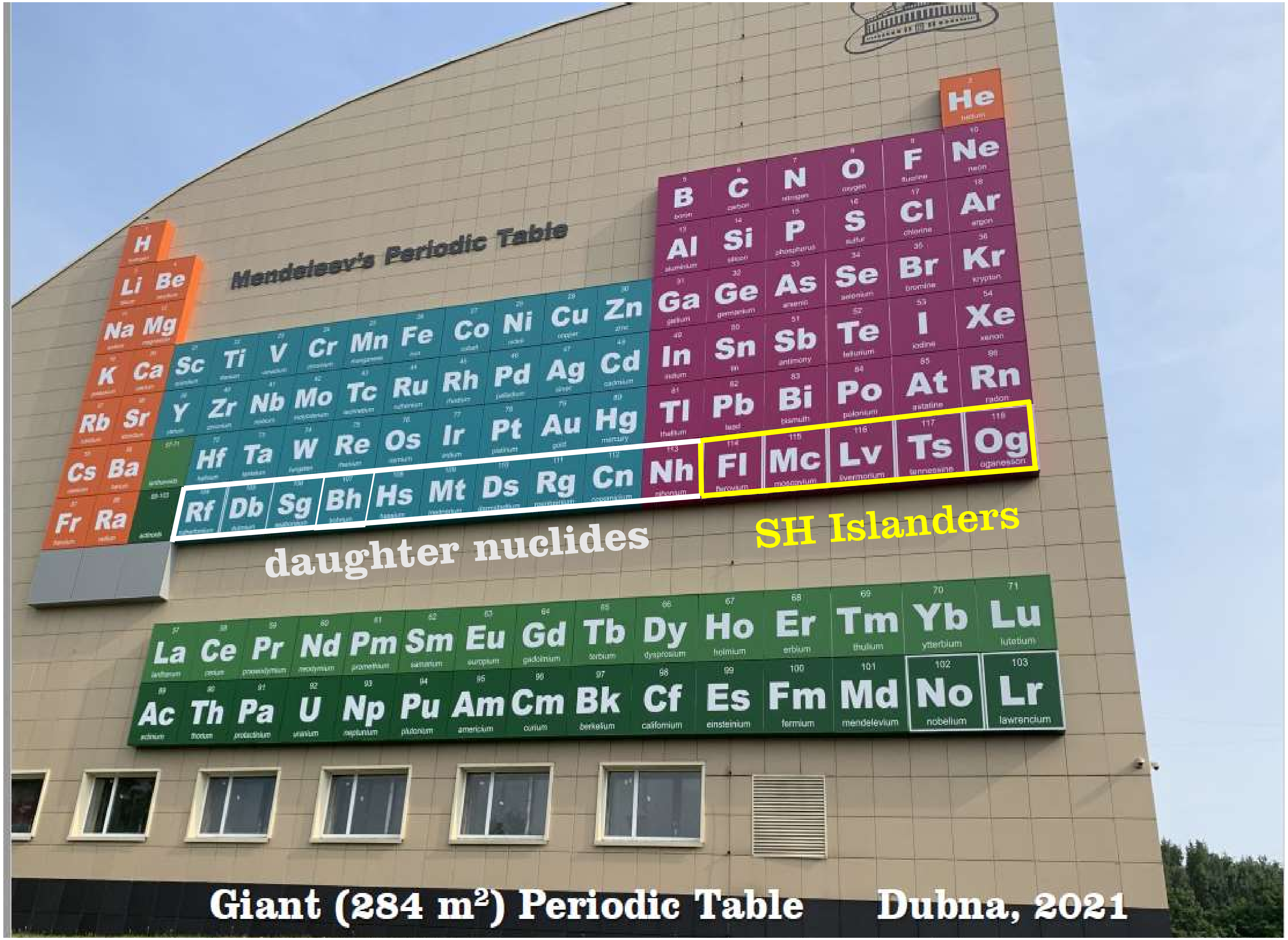
-6
-2
2
6
10
14
lgT, sec
Towards the Island of Stability
GSI, RIKEN
Dubna
1999-2016
Флеровий 114 Fl Flerovium
Московий 115 Mc Moscovium
Ливерморий 116 Lv Livermorium
Теннессин 117 Ts Tennessine
Оганесон 118 Og Oganesson
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

UNESCO-Russia Mendeleev Prize

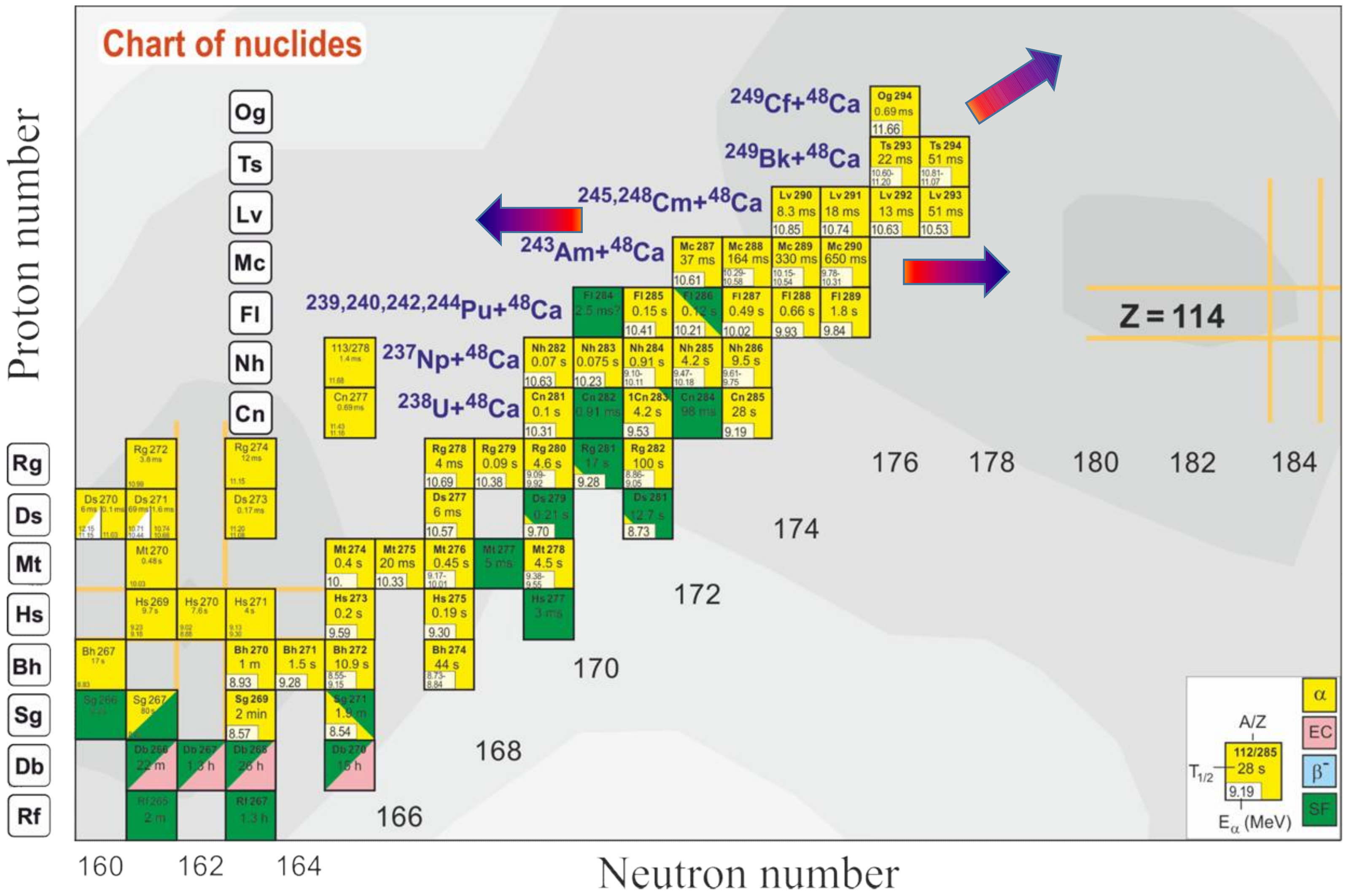
On 3 November, laureates of the UNESCO-Russia Mendeleev International Prize in the Basic Sciences were announced.

Awarding ceremony
November, 15
UNESCO Headquarters in Paris

The first laureate of the Prize is Scientific Leader of the Flerov Laboratory of Nuclear Reactions JINR Yuri Oganessian "*to acknowledge his breakthrough discoveries extending the Periodic Table and for his promotion of the basic sciences for development at the global scale*".


Mendeleev's Periodic Table
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
daughter nuclides
SH Islanders
Giant (284 m²) Periodic Table
Dubna, 2021

Fusion reactions: *left, right or up?*



Factory of superheavy elements

The center for future superheavy element research

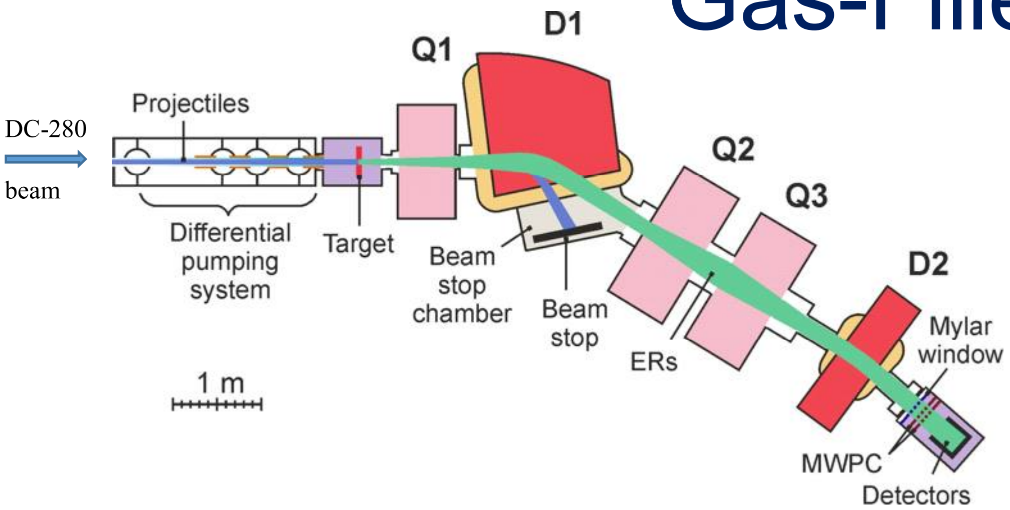
Cyclotron DC-280
Factory of superheavy elements

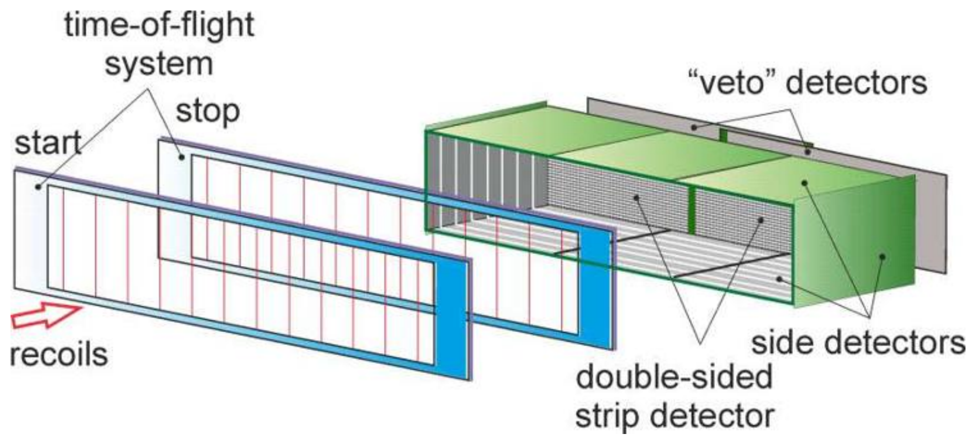
Beam of ^{48}Ca

Achieved Intensity:
$4.6 \cdot 10^{13}$ ions/s

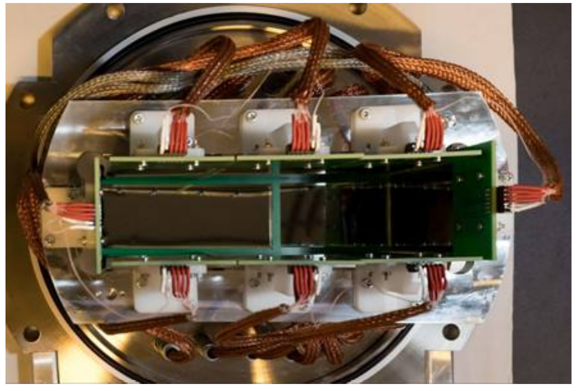
Efficiency:
~50%

Gas-Filled Separator, **DGFRS-2**





^{242}Pu 24-cm target wheel
12 sectors



48×220 DSSD &
60×120 SSSD
Digital and analog electronics

The first experiment: synthesis of moscovium isotopes (element 115)

$^{48}Ca + ^{243}Am \rightarrow ^{291}Mc^*$

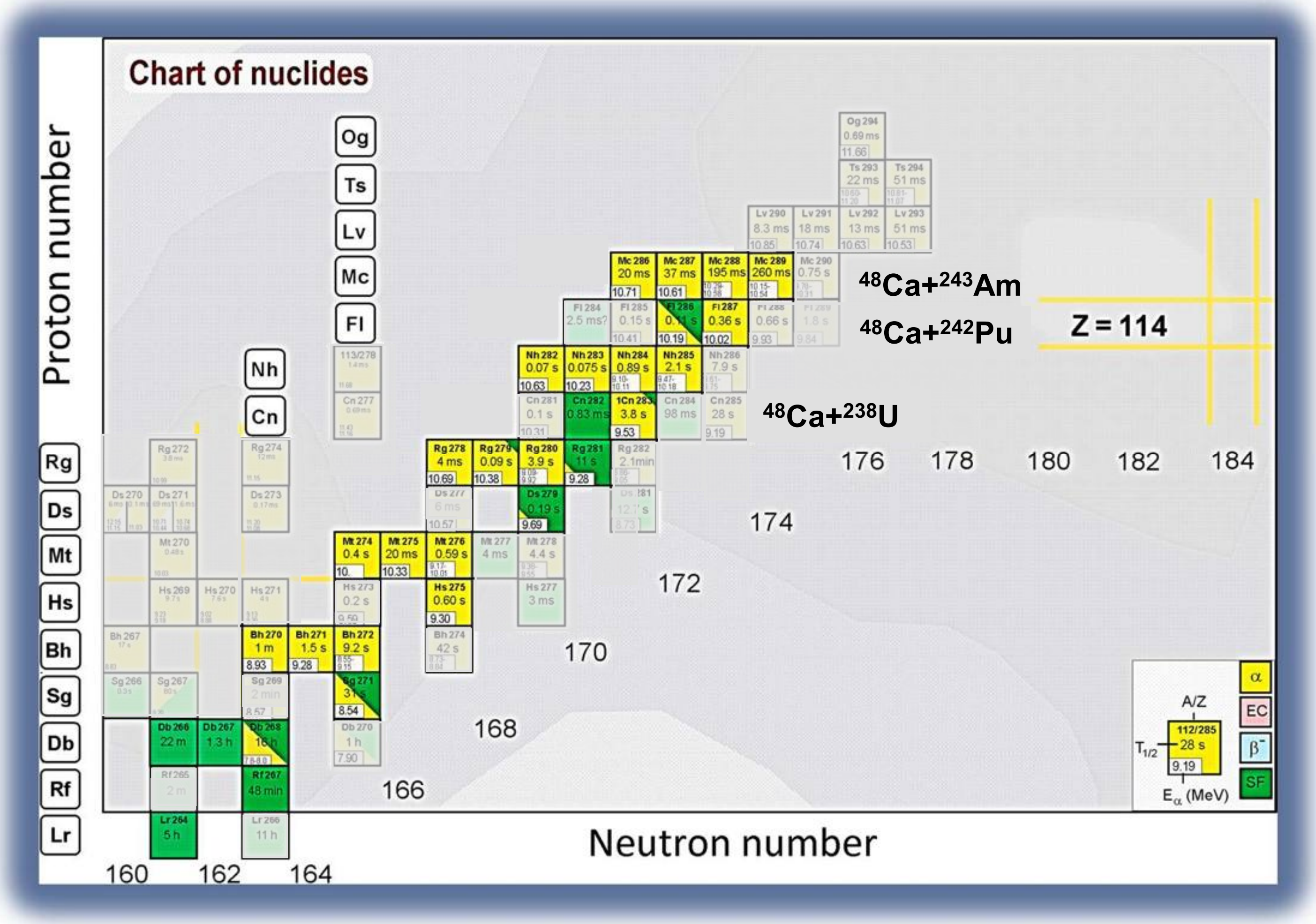
E (MeV)	239.1	240.9	242.0	243.9	251.0	259.0	**total**	*before*
^{286}**Mc** (5*n*)	-	-	-	-	0	1	**1**	*0*
^{287}**Mc** (4*n*)	-	-	2	-	1	1	**4**	*3*
^{288}**Mc** (3*n*)	9	16	52	30	0	3	**110**	*31*
^{289}**Mc** (2*n*)	-	1	4	5	-	-	**10**	*18*

Summary of experiments @ Superheavy Element Factory in 2020-2023

Experiments:

$^{243}Am + ^{48}Ca \rightarrow ^{291}Mc^*$
$^{242}Pu + ^{48}Ca \rightarrow ^{290}Fl^*$
$^{238}U + ^{48}Ca \rightarrow ^{286}Cn^*$
$^{232}Th + ^{48}Ca \rightarrow ^{280}Ds^*$

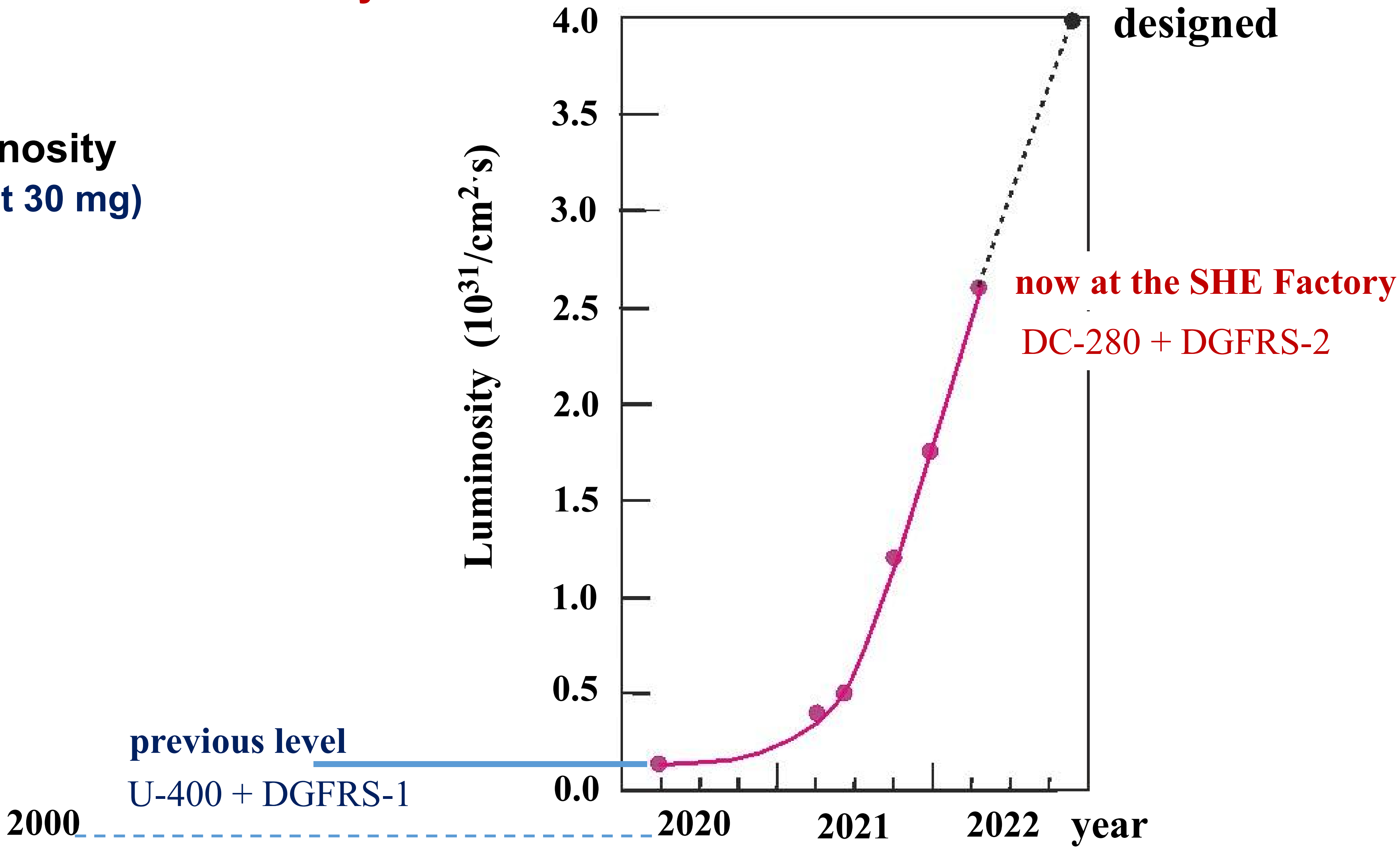
- 239 new events of synthesis of superheavy nuclides;
- Decay properties 36 isotopes;
- New isotopes: ^{286}Mc, ^{264}Lr, ^{275}Ds, ^{276}Ds, ^{272}Hs , ^{268}Sg;
- New decay modes: ^{268}Db (alpha-decay), ^{279}Rg (spontaneous fission);
- Indication of the 1st excited state in ^{286}Fl;
- Test of target stability up to 6.5 pμA of ^{48}Ca;



Progress at SHE-Factory

Luminosity

(target 30 mg)



by Yu. Oganessian

Perspectives

Synthesis of new elements @ SHE Factory

$^{54}Cr + ^{248}Cm \rightarrow 3n +$ **$^{299}120$**

$^{50}Ti + ^{251}Cf \rightarrow 3n +$ **$^{298}120$**

$^{50}Ti + ^{249}Bk \rightarrow 3n +$ **$^{296}119$**

TARGETS

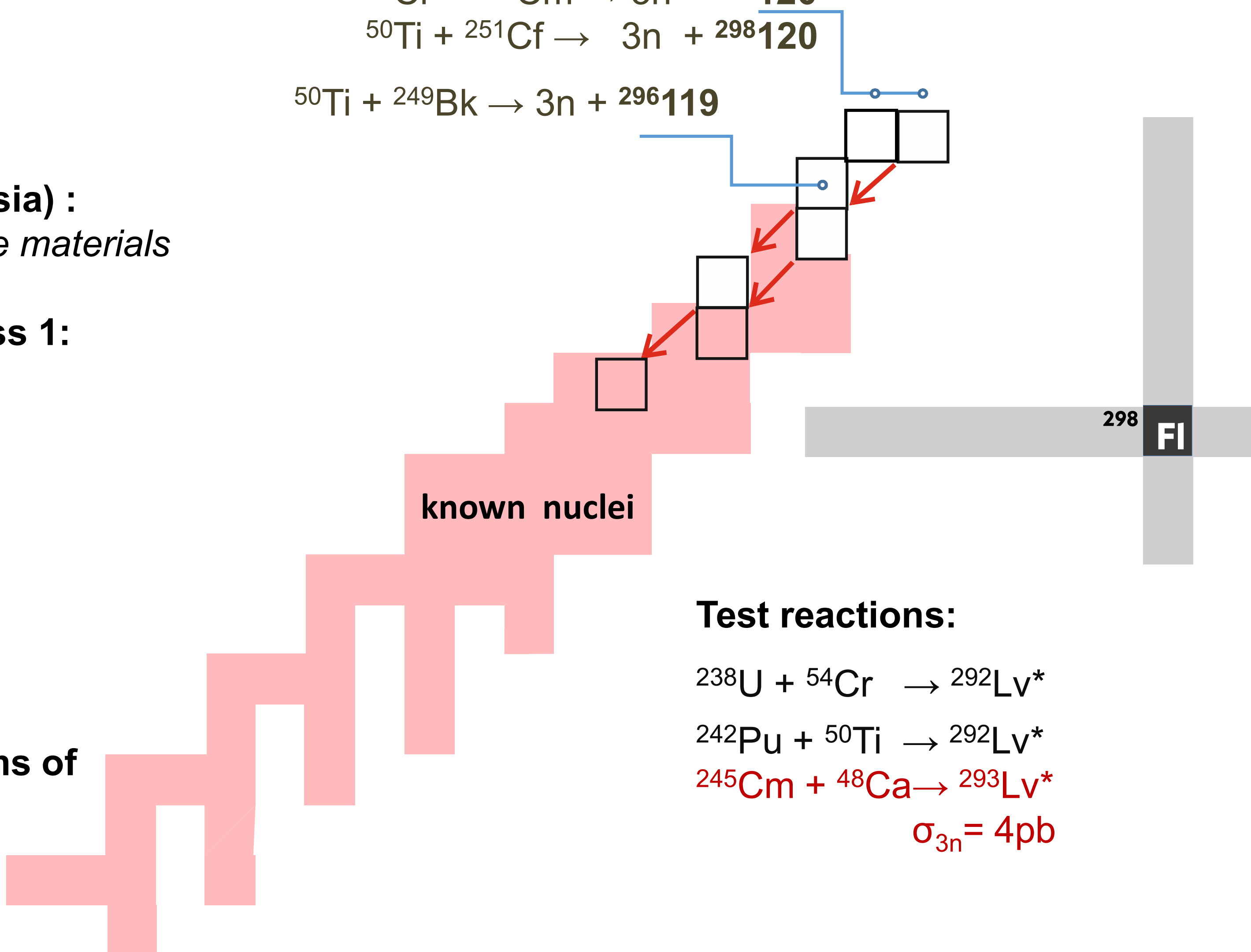
- **Cooperation with Rosatom (Russia) :**
  Isotopically enriched heavy actinide materials

- **Radiochemical laboratory of class 1:**
  Stability studies &
  Manufacturing and regeneration

BEAMS

- **Production of high-intensity beams of ^{50}Ti, ^{54}Cr and others**

- **New ECR-28 GHz (2024)**



Test reactions:

$^{238}U + ^{54}Cr \rightarrow ^{292}Lv^*$

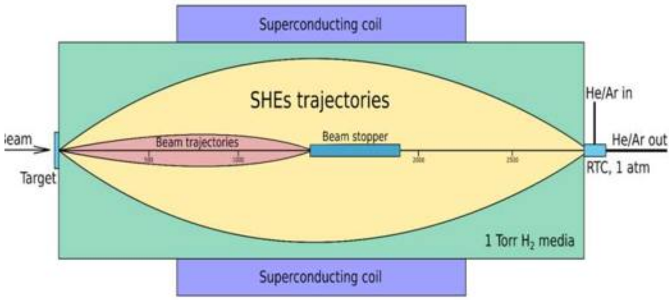
$^{242}Pu + ^{50}Ti \rightarrow ^{292}Lv^*$

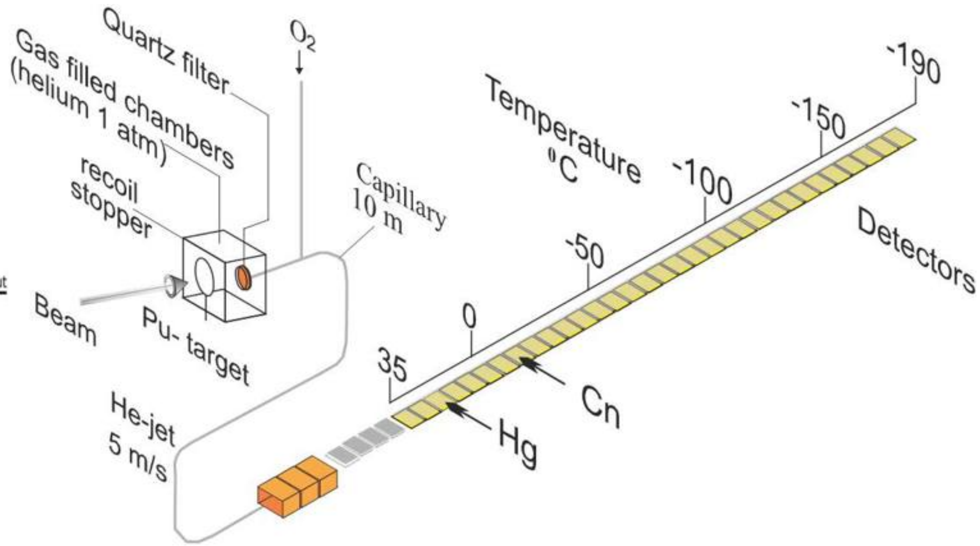
$^{245}Cm + ^{48}Ca \rightarrow ^{293}Lv^*$

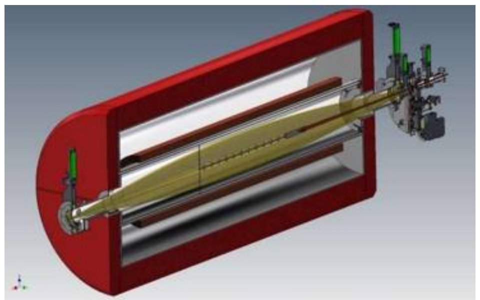
$\sigma_{3n} = 4pb$

Future of SHE Chemistry

Fixed blades for beam suppression







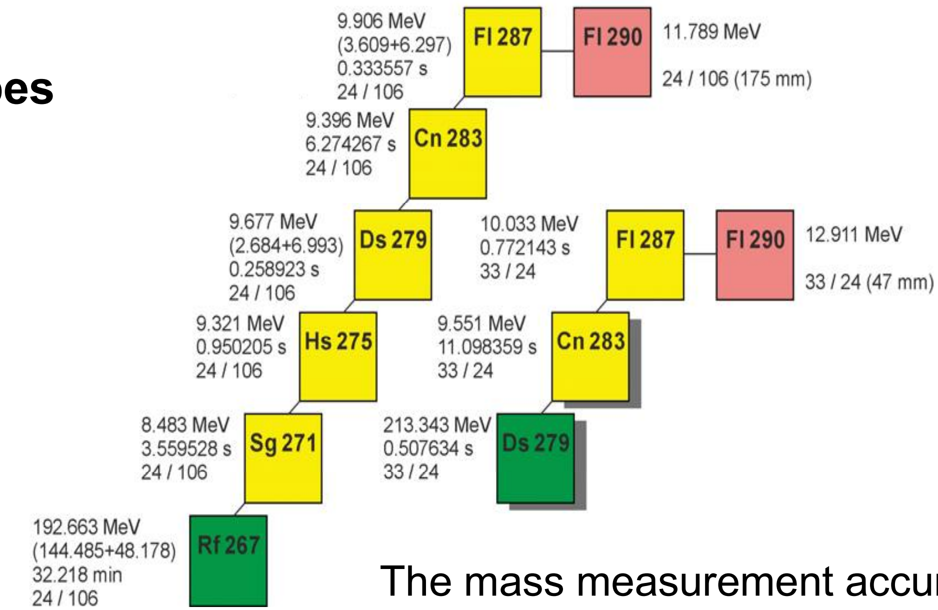
GASSOL – Solenoid-based separator (2025)

- *Stopping SH atoms in a small volume of 1-2 cm^3*
- *Chemistry of short-lived SHE $T_{1/2} \geq 30$ ms (up to elements 116-117)*

Precise mass measurements of SH isotopes

Measuring masses of SH isotopes with accuracy 10^{-7} (30 кeV)

$T_{1/2} < 0.5$ s
Production rate ≤ 1 event/day
Background rate ≥ 1 event/s



Requirements for a facility:
- High rate of analysis;
- Low losses;
- High degree of purification;
- Accuracy 10^{-7} (30 кeV);
- Mass range 266 – 294.

The mass measurement accuracy depends on
- Mass resolution R_m
- Statistics N

$$\frac{\delta m}{m} \approx \frac{1}{2R_m\sqrt{N}}$$

$\delta m/m = 10^{-7}$, N = 5 => $R_m = 2\ 000\ 000$

The only type of spectrometers gives an opportunity to reach Rm > 1 000 000 at the analysis time < 0.5 s: **MR-TOF Mass-Analyzer**

M.I. Yavor, Journal of Instrumentation, ***17*** *(2022) 1103*

Spectroscopy of SH isotopes (SHE factory)

$^{48}Ca + ^{242}Pu \rightarrow ^{287}Fl + 3n$

$^{48}Ca + ^{243}Am \rightarrow ^{288}Mc + 3n$

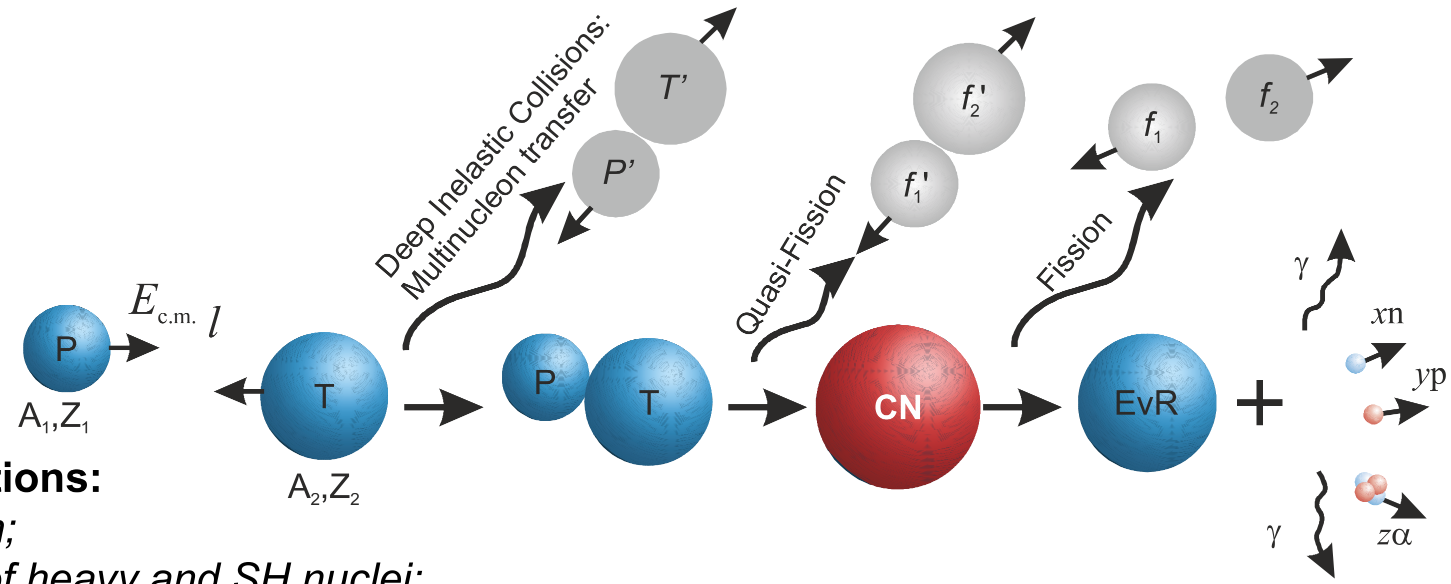
Cross section ~ 10 pbarn;
Target thickness ~ $1.5x10^{18}$ at/cm^2;
Beam intensity of ^{48}Ca ~ $3.3x10^{13}$ pps (5 pμA);
$\varepsilon_{transmission}$ ~ 50 %;

100 days → ~300 events

300 chains → 250 gamma quanta detected.

Nuclear reactions

Main tasks in nuclear reactions studies @ U400R



- **Multinucleon transfer reactions:**
  Study of reaction mechanism;
  Production of new isotopes of heavy and SH nuclei;
  Study of properties of new nuclei.

- **Decay spectroscopy of heavy nuclei:** *actinides and light transactinides*

- **Study of fusion-fission and quasifission reactions leading to heaviest nuclei**

- **Low-energy and spontaneous fission of heaviest nuclei**

- **Study of nuclei at high excitation energies (several hundred of MeV)**

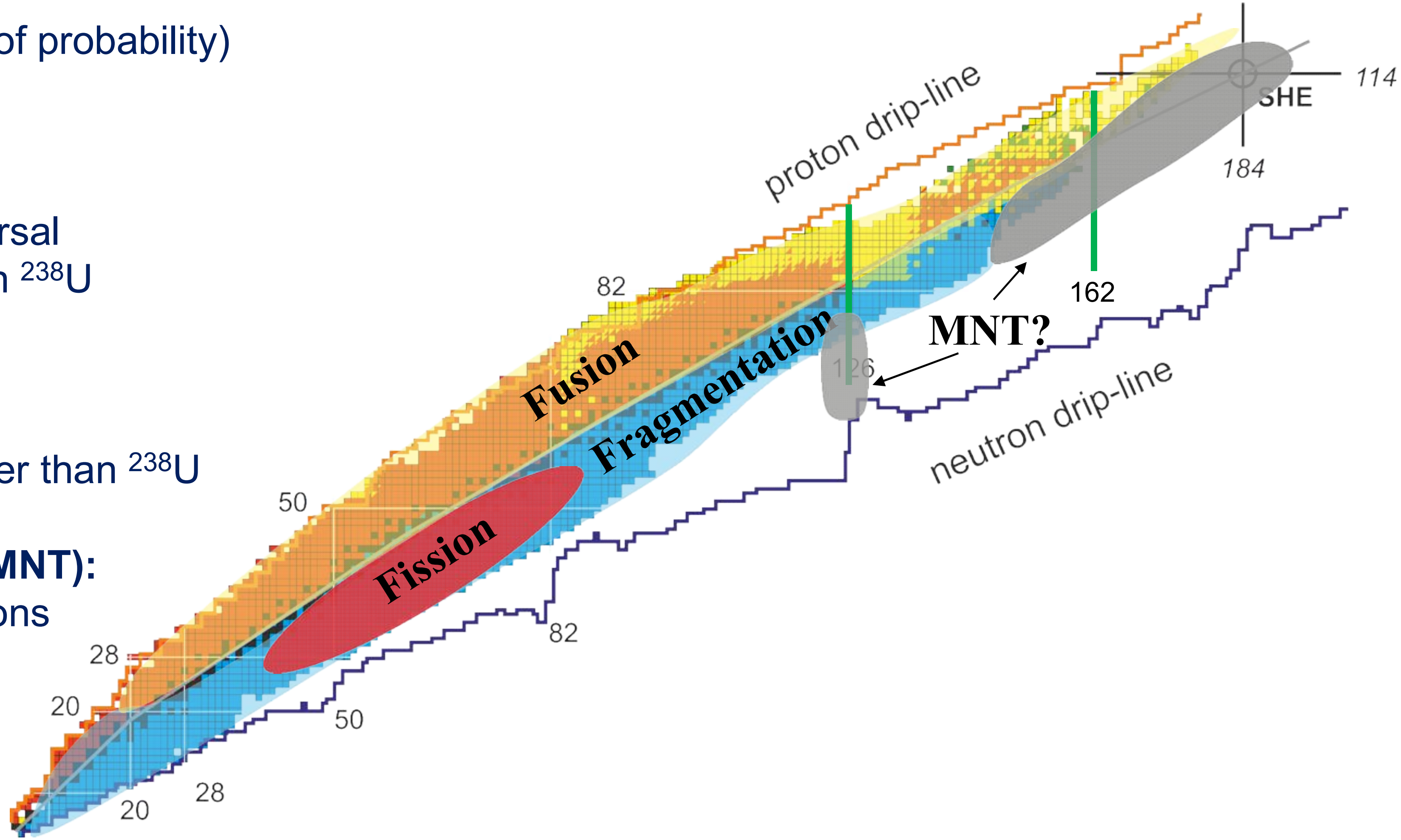
Methods of synthesis of new nuclei

Fusion:
+ any element (question of probability)
- lack of neutrons

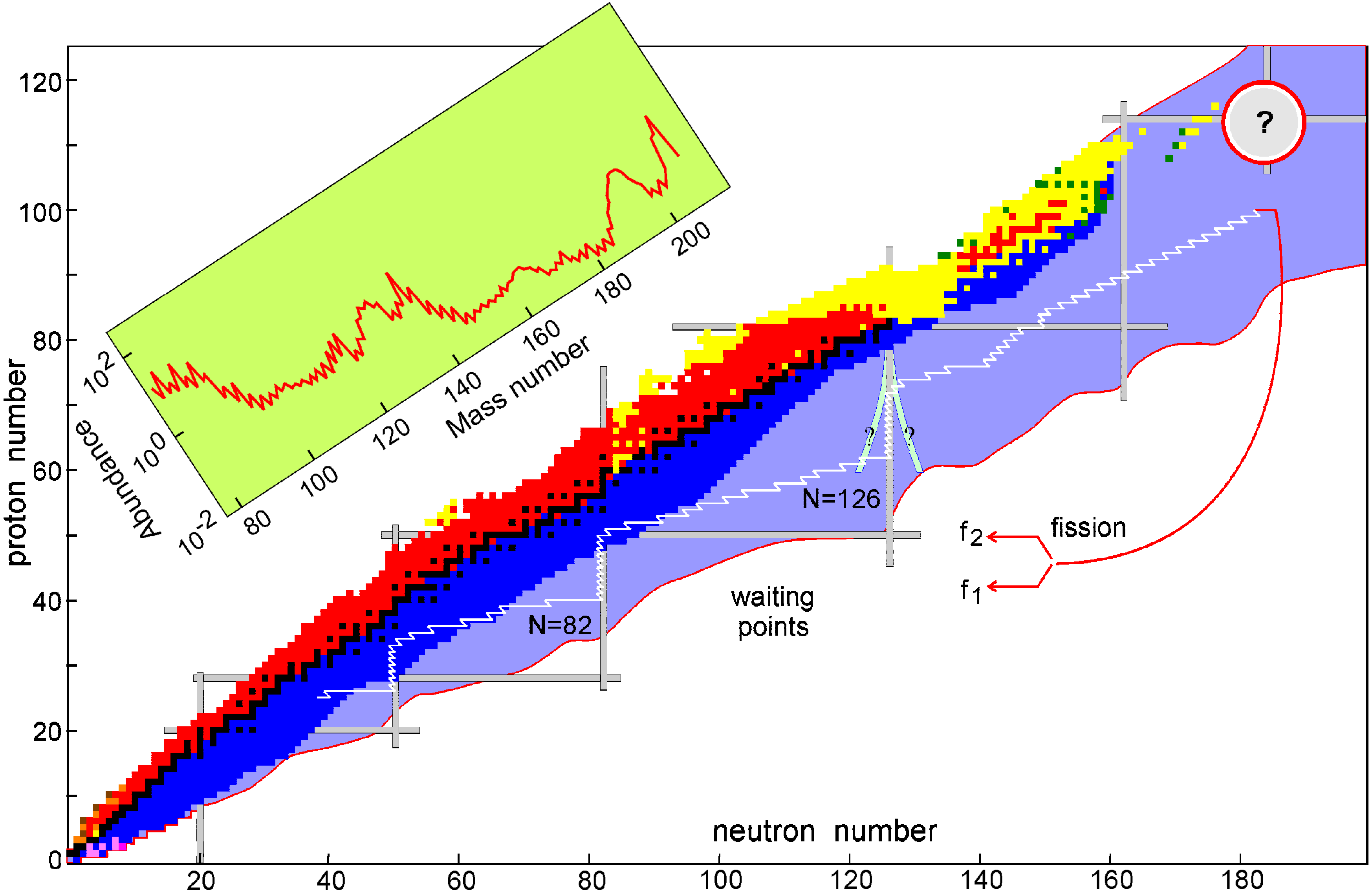
Fragmentation:
+ very efficient and universal
- products are lighter than ^{238}U

Fission:
+ neutron-rich products
- products are much lighter than ^{238}U

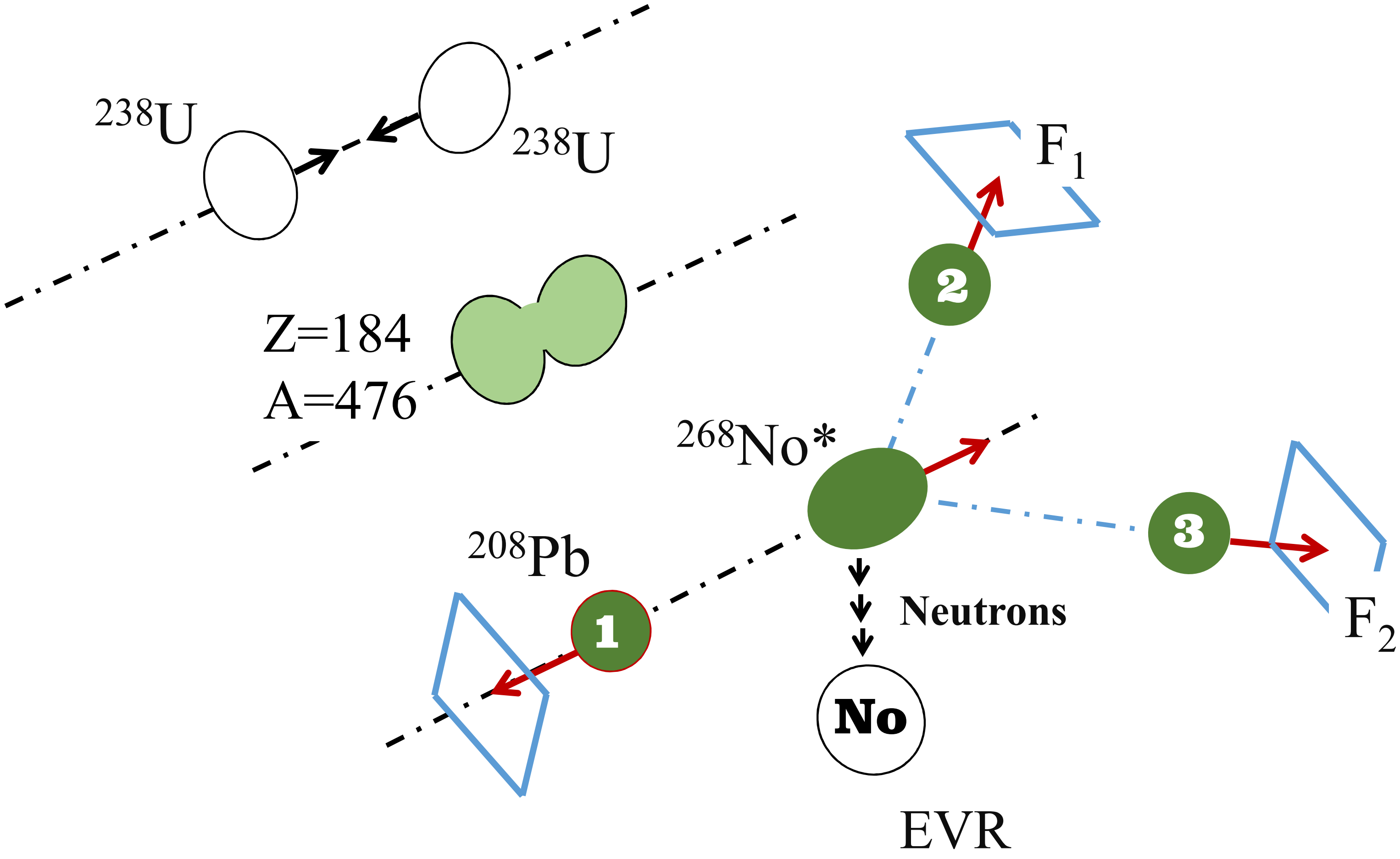
Multinucleon transfer (MNT):
+ a way to unknown regions
- very, very complicated technically



r - процесс нуклеосинтеза
и замкнутая нейтронная оболочка N ~ 126



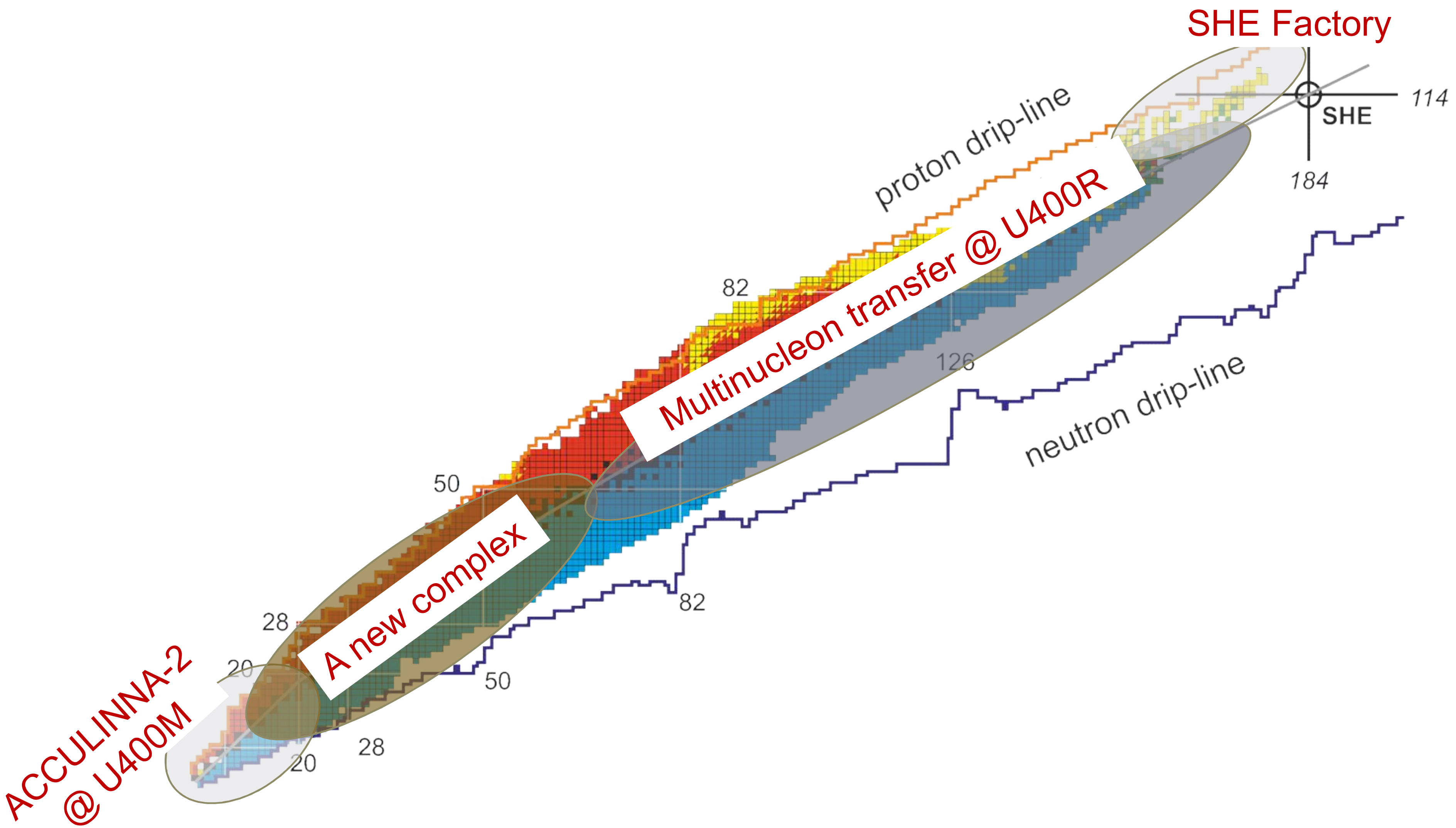
Studying the $^{238}U + ^{238}U$ reaction



slide by Yu. Oganessian

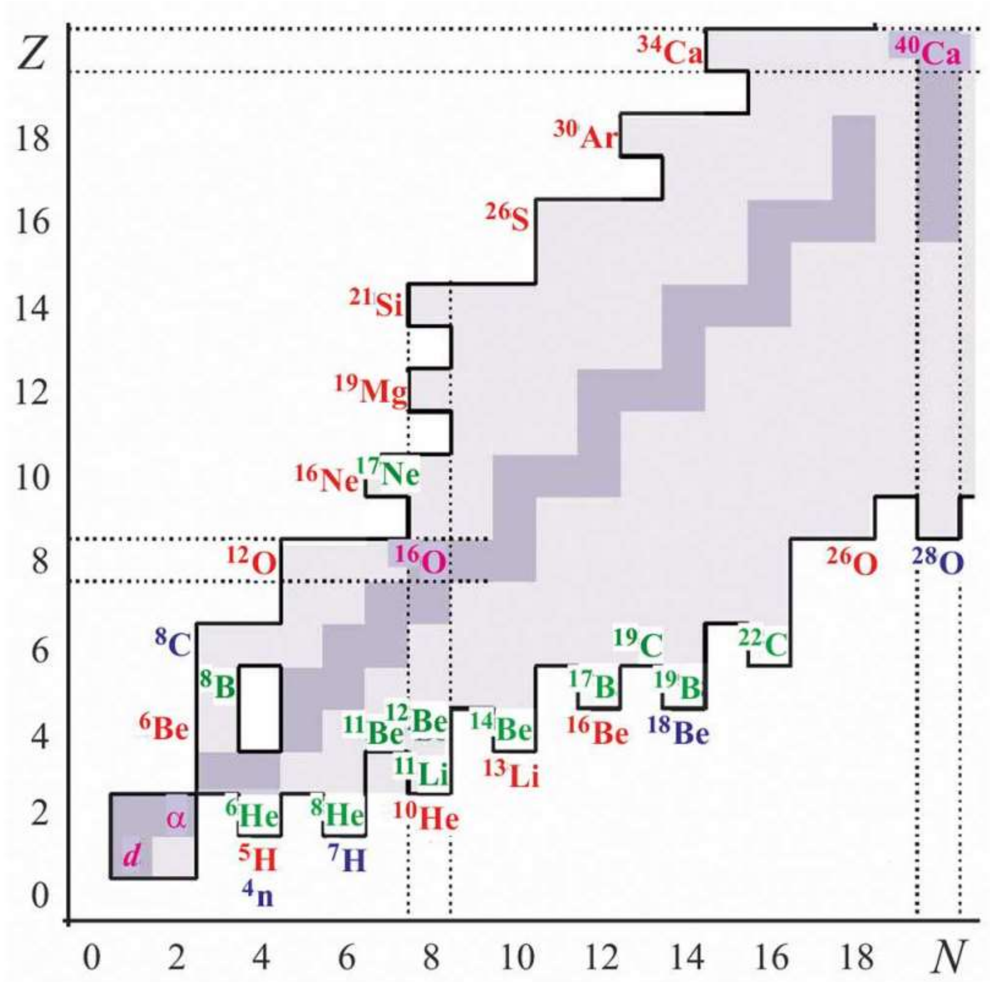
Study of exotic nuclei
close and beyond the nucleon stability limits

Rare isotope research: long-term perspectives



Experimental program with radioactive ion beams

- Nucleon haloes, neutron skins
- Exotic multi-neutron decays (2n virtual states, 2n and 4n radioactivity)
- Soft excitation mode
- New magic numbers and intruder states
- Two proton radioactivity
- Spectroscopy of exotic nuclei
- Cluster states
- Reactions with halo nuclei
- Astrophysical applications

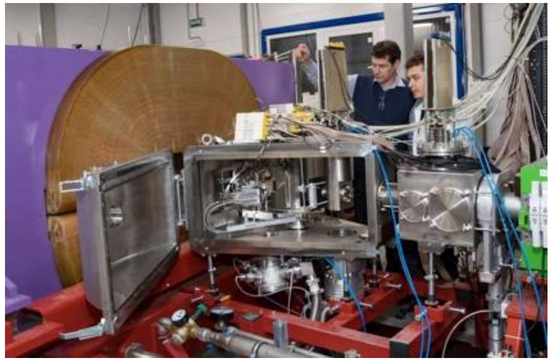


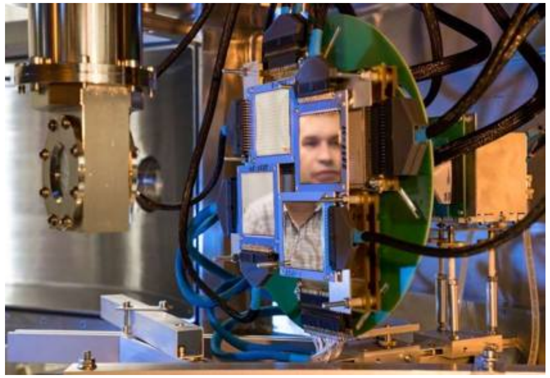
Fragment separator ACCULINNA-II @ U400M

Under modernization until mid of 2023
2023-2030 - operation

Tasks:

- Nucleon halo, neutron skin;
- Exotic decays:
  β-delayed, 2p, 2n radioactivity, etc.;
- Soft excitation mode;
- New magic numbers;
- Spectroscopy of exotic nuclei;
- Cluster states;
- Reactions with RIBs;
- Astrophysical applications.





ACCULINNA-II

Applied research with heavy-ion beams

IC-100 CYCLOTRON

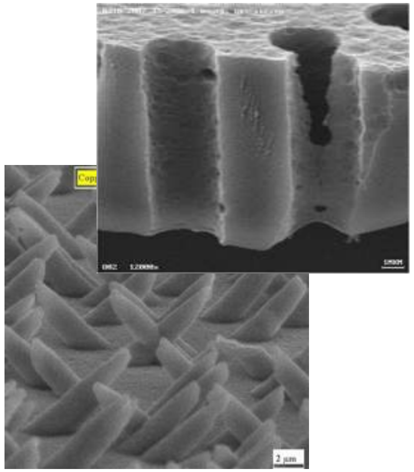
APPLIED RESEARCH

parameters	
Accelerated ions	$^{22}Ne^{+4}$ $^{40}Ar^{+7}$ $^{56}Fe^{+10}$ $^{86}Kr^{+15}$ $^{127}I^{+22}$ $^{132}Xe^{+23}$ $^{132}Xe^{+24}$ $^{182}W^{+32}$ $^{184}W^{+31}$ $^{184}W^{+32}$
A/Z ratio	5.5 – 5.95
Ion energy	0.9-1.2 MeV/A
Pole diameter	1 m
Vacuum	$5\cdot10^{-8}$ Torr
$^{86}Kr^{15+}$ beam intensity	$1.4\cdot10^{12}$ pps
$^{132}Xe^{23+}$ beam intensity	~ 10^{12} pps

Commissioned: 1985
Reconstructed: 2002

Setups:

- polymer film irradiation unit with uniform implantation over a 600x200 mm target
- box for material science research



MICROTRON MT-25

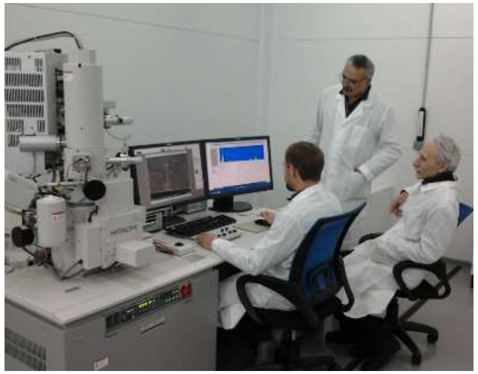
parameters	
Energy range	5 to 25 MeV
Pulsed beam current	20 mA
γ-ray flux	10^{14} pps
Thermal neutron flux	10^{9} pps cm^{-2}
Fast neutron flux	10^{12} pps

Applications:

- γ-activation analysis
- neutron activation analysis
- isotope production for analytical purposes
- study of nuclear reaction induced by γ-quanta

NANOLAB

Scanning electron microscopy



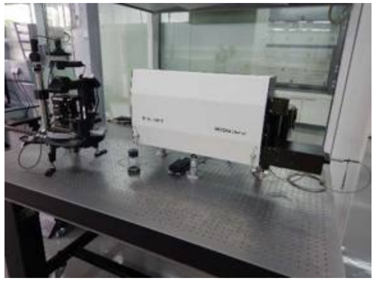
FESEM Hitachi SU8020
Resolution of 1 nm at 15 kV
X-ray element microanalysis (EDS)
Deceleration mode (500 eV)

SEM Hitachi S3400N
Resolution of 1 nm at 15 kV
EDS, WDS
Electron backscattering diffraction

X-ray photoelectron spectroscopy K-Alpha

Chemical analysis of thin layers and surfaces

NTEGRA Spectra – Atomic force microscopy (AFM)/ Confocal Raman & Fluorescence



Studies of nanostructures induced by single ion impact on the surface of solids; depth-resolved Raman and photoluminescence spectra

Multi-functional chemical laboratory

(studies of heavy ion irradiation effects, modification of materials, polymers, membranes)

Capillary porometer Porolux

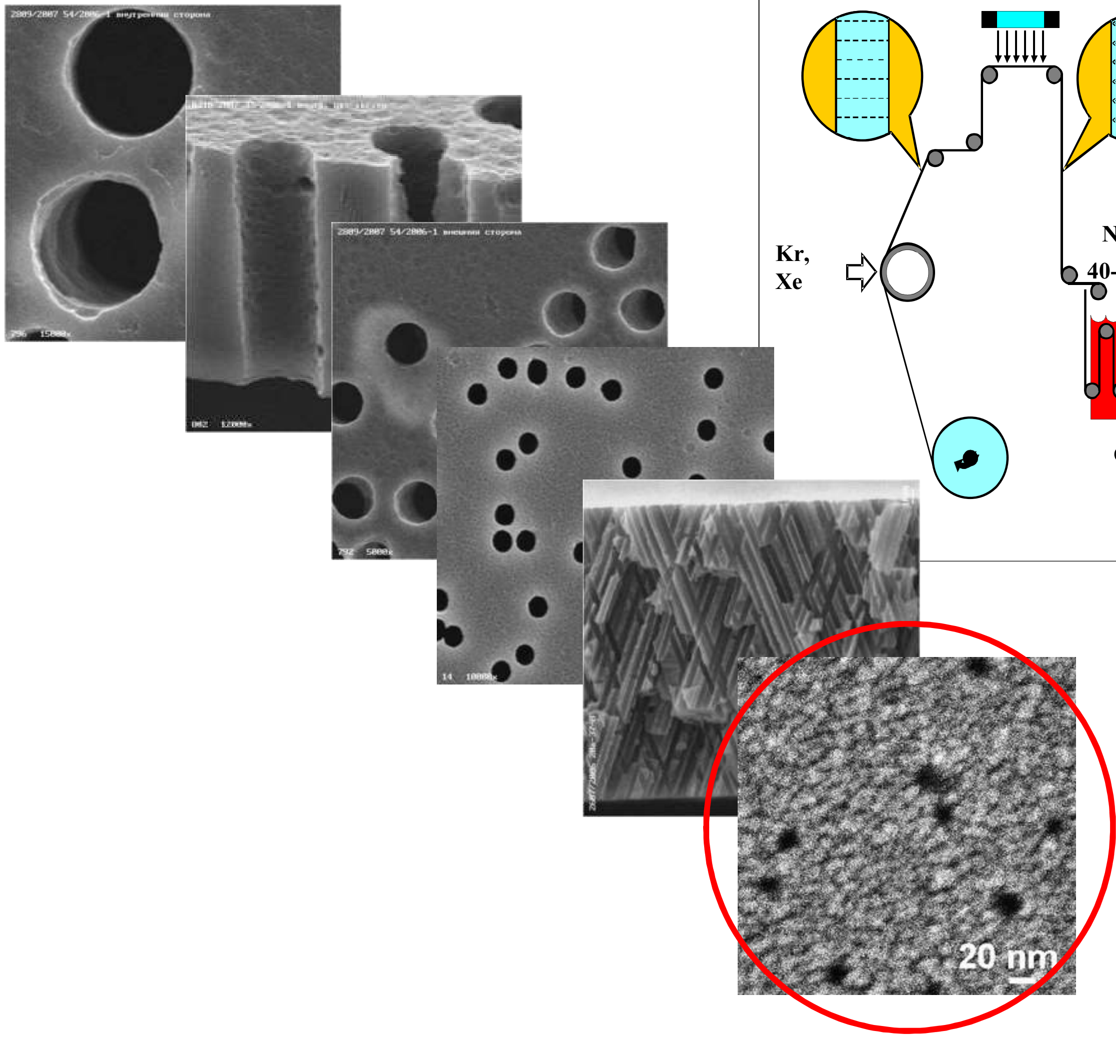
Precise characterization of ultra- and microfiltration membranes

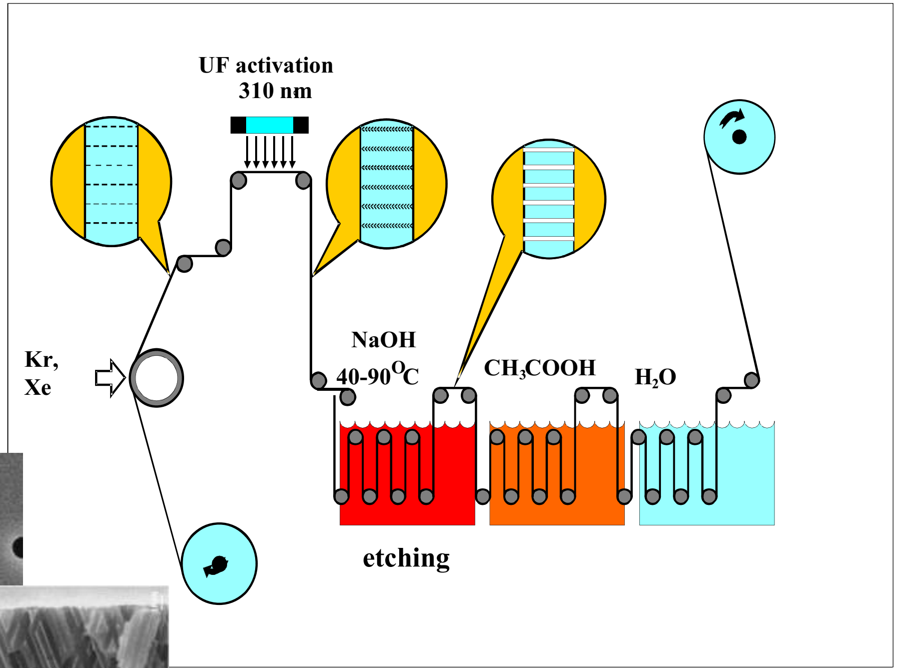
KRUESS DSA100 system

Investigations of static and dynamic wetting phenomena

Production of track membranes (IC-100)

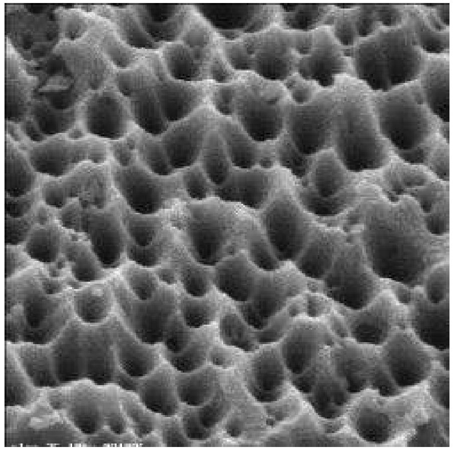
Micrometers

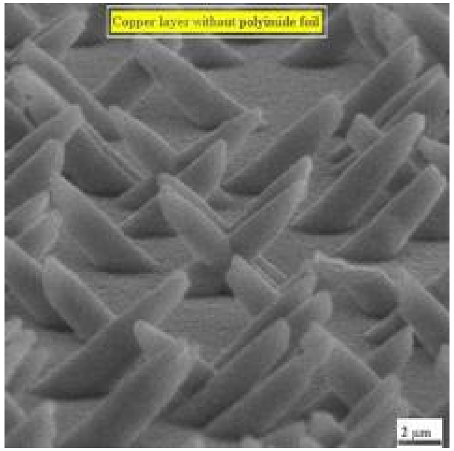




Nanometers

Accelerator-born nanostructures





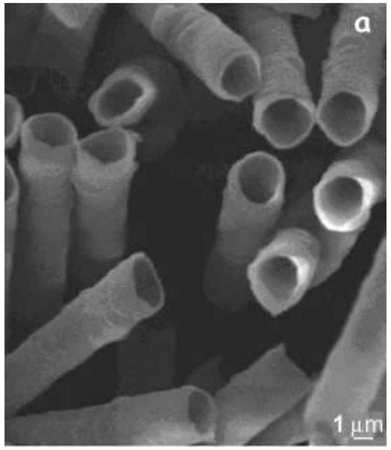
new composite materials:

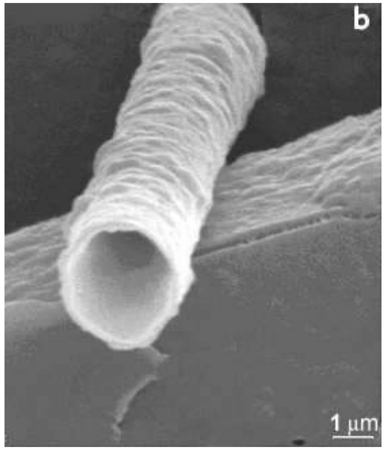
- extended layers adhesion strength
- increased thermal resistance
- flexible printed circuit boards

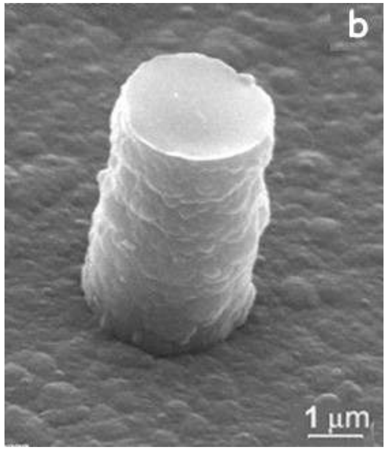
Polymer composites produced with the use of track membranes

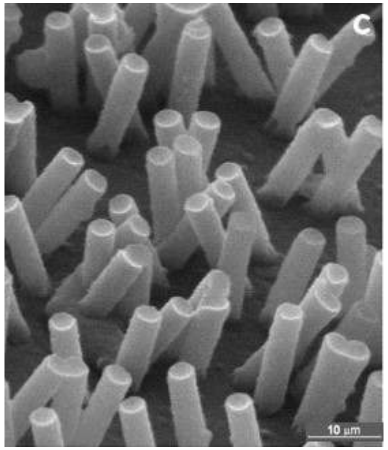
nanotubes

nanowires





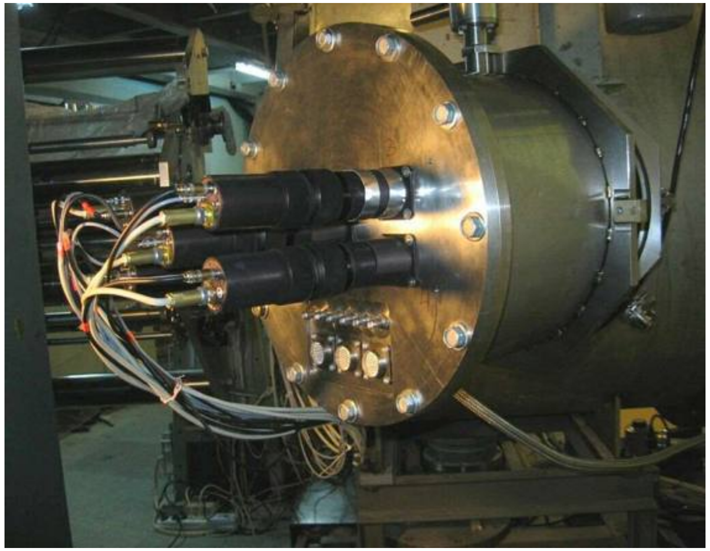




Radiation Hardness Tests For Electronic Components

Development of radiation-proofed electronic components is the first priority task of the modern high-class electronic industry.

Long-distance space flights, long-lived sputniks, etc. are extremely critical to the quality of electronic chips.



Thank you for attention!