Synthesis of superheavy elements

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Basic directions of researches at FLNR

1. Heavy and superheavy nuclei

- Synthesis and study of properties of superheavy elements
- Chemistry of new elements
- Fusion-fission and multi-nucleon transfer reactions
- Mass-spectrometry and nuclear spectroscopy of SH nuclei

2. Light exotic nuclei

- Properties and structure of light exotic nuclei
- Reactions with exotic nuclei

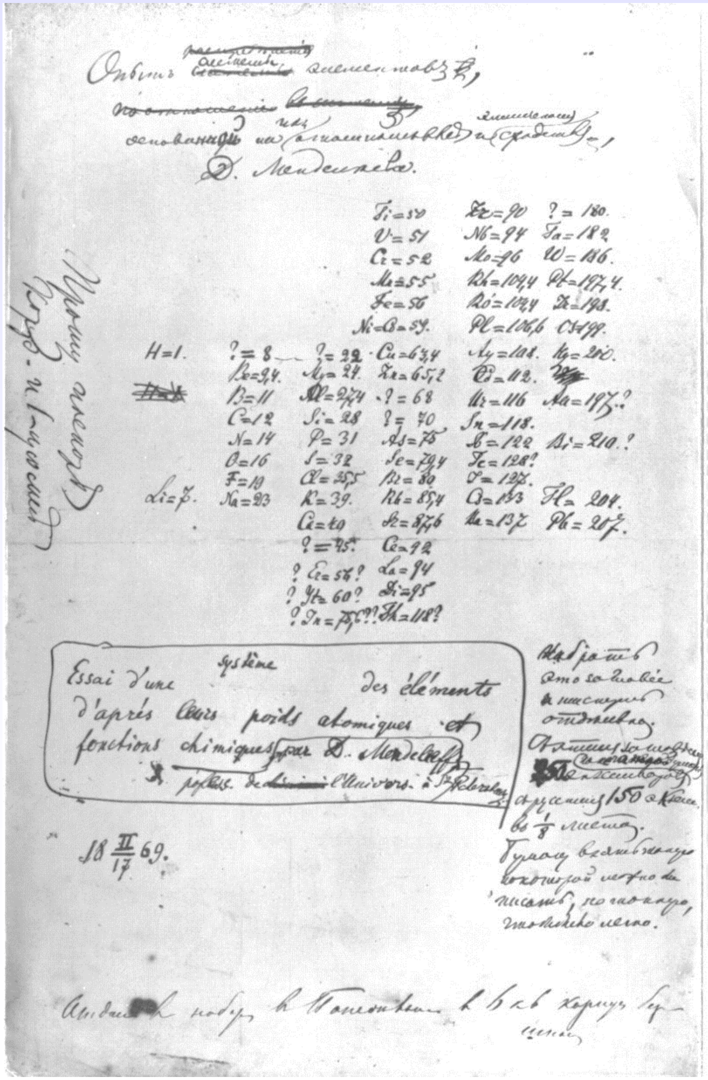
3. Radiation effects and physical bases of nanotechnology

4. Accelerator technology

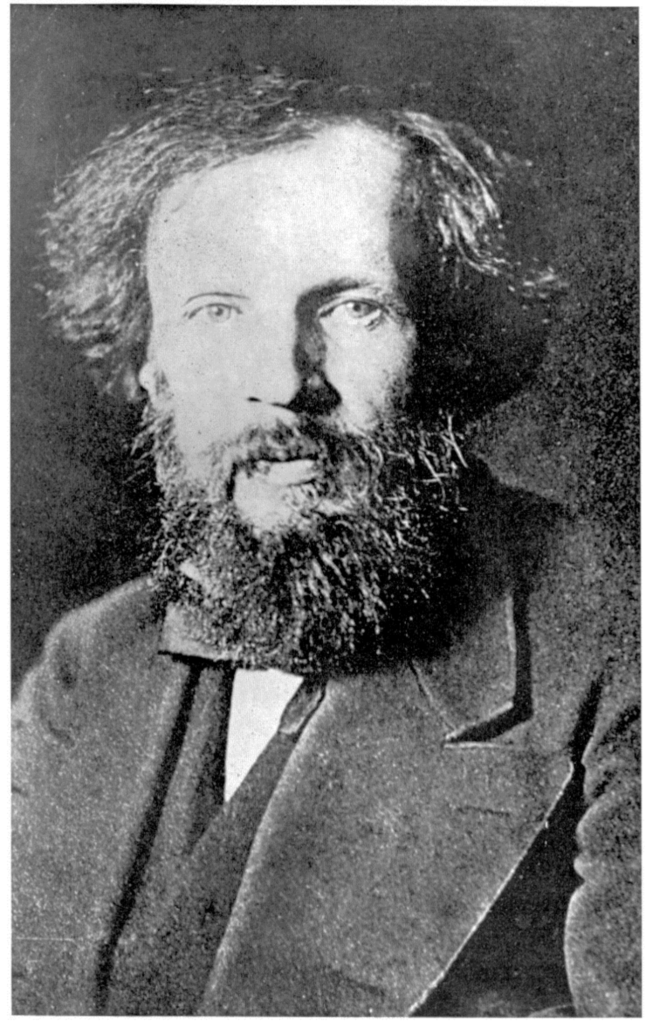
OUTLINES

What are the SHE?
What do we know about SHE?
Targets and projectiles.
SHE – factory.
High-current cyclotron DC-280.
New facilities.
Light exotic nuclei.
Applied research.
Conclusions.

Periodic table of the elements
Dmitri Mendeleev (1869)


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

18 II/17 69.



1934: search for transurane

$$^{238}_{92}U + n \longrightarrow {}^{239}_{92}U^* \longrightarrow {}^{239}_{93}Nn + e^- + \bar{v}$$

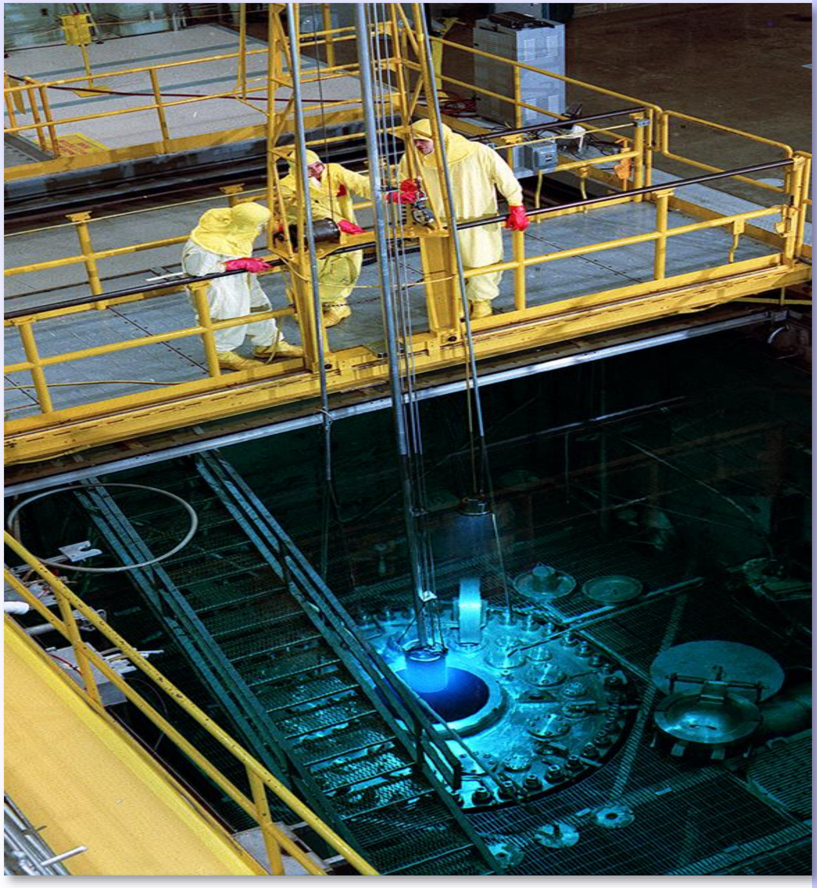
Otto Hahn und Lise Meitner

Irradiation of targets at HFIR reactor (Oak Ridge)

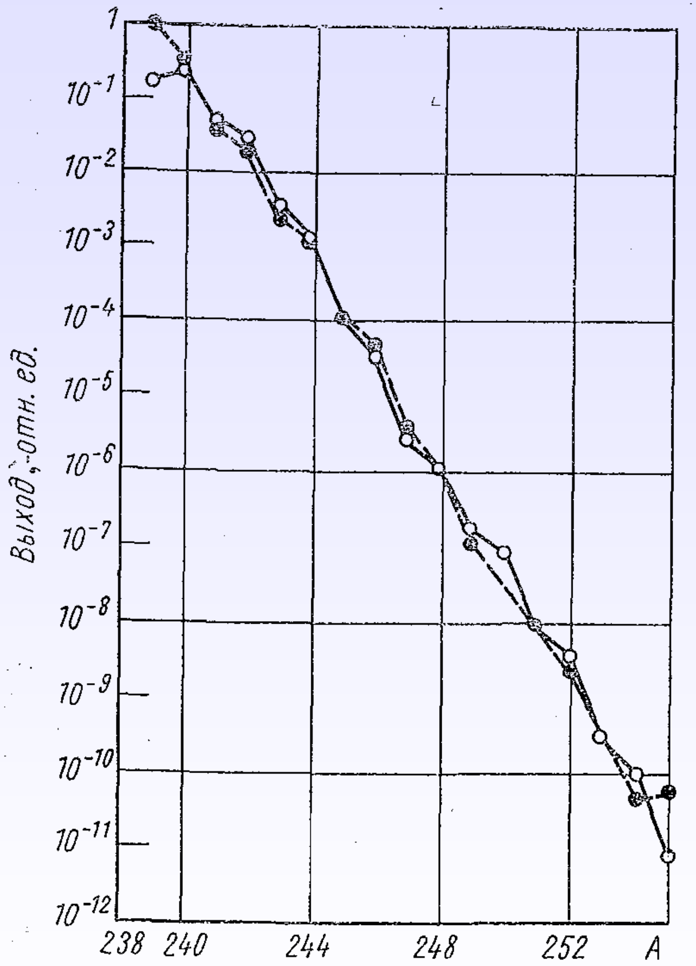
$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{239}_{92}\mathrm{U} \xrightarrow[23.5\ \mathrm{min}]{\beta^-} ^{239}_{93}\mathrm{Np} \xrightarrow[2.3565\ \mathrm{d}]{\beta^-} ^{239}_{94}\mathrm{Pu}$$

$$^{239}_{94}\mathrm{Pu} \xrightarrow{(\mathrm{n},\gamma)} ^{240}_{94}\mathrm{Pu} \xrightarrow{(\mathrm{n},\gamma)} ^{241}_{94}\mathrm{Pu} \xrightarrow[14{,}35\ \mathrm{a}]{\beta^-} ^{241}_{95}\mathrm{Am}\ (\xrightarrow[432{,}2\ \mathrm{a}]{\alpha} ^{237}_{93}\mathrm{Np})$$

- **Irradiation in the HFIR flux trap**
  - **Thermal-neutron flux of 2.5×10^{15} neutrons/cm²·s**
  - **31 target positions (10–13 targets typically irradiated)**
  - **Produces ~35 mg ^{252}Cf per target (smaller quantities of Bk, Es, Fm)**

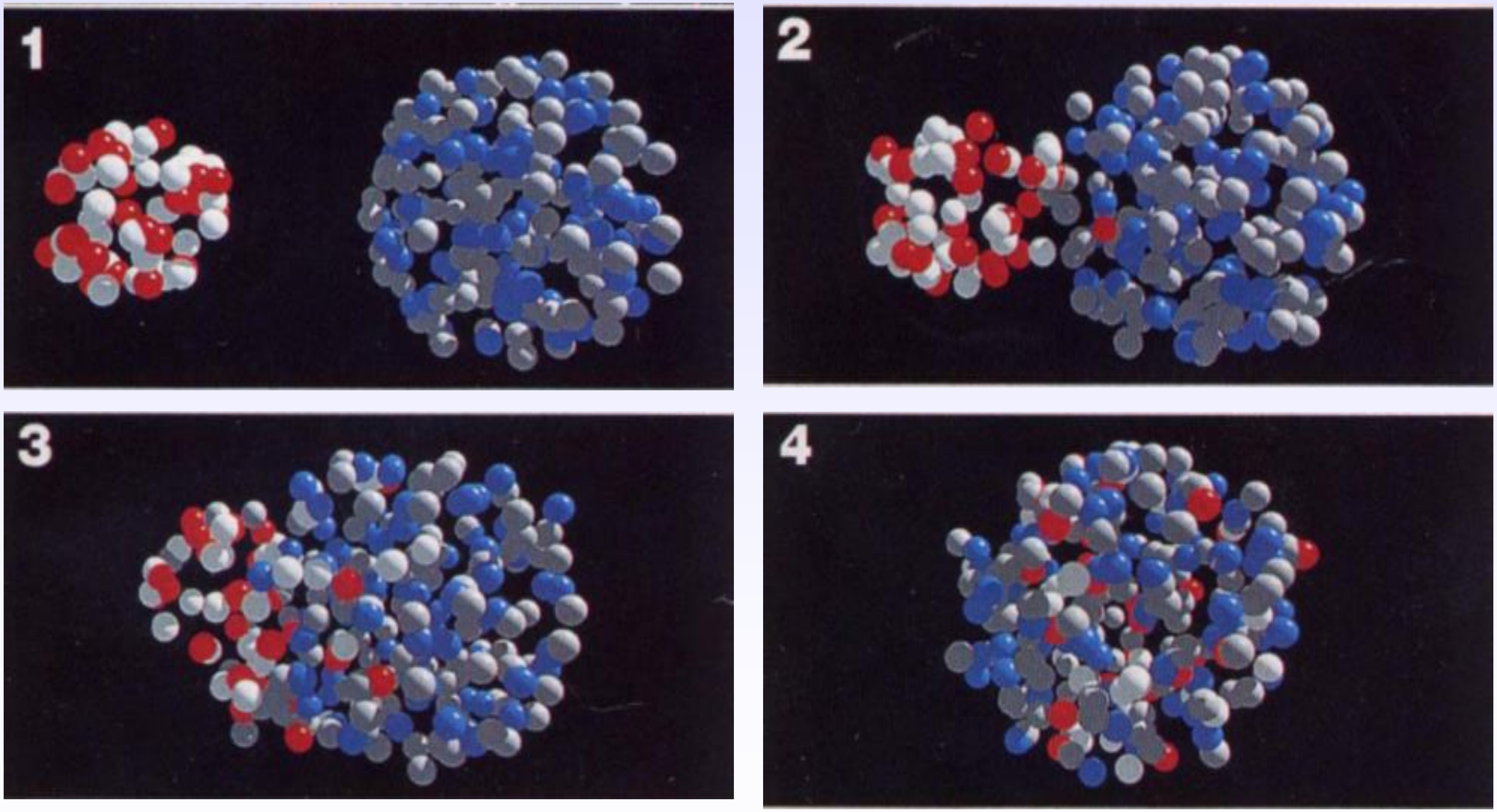


R-process



Explosion 20 кТ → $2 \cdot 10^{24}$ fissions;
$N_f = \exp\{n-1\}$ → n = 56 → T = 336 ns;
last 18 ns → 90 % of neutrons;
thermonuclear explosion: 50 ns;
total time: < 100 ns, total neutron flux: $1.2 \cdot 10^{24}$ n·cm^{-2}
But… collection efficiency $10^{-8} \div 10^{-9}$!

Complete Fusion $_{92}U + _{7}N \rightarrow _{99}Es$
instead of $U + 14n \rightarrow 7\beta \rightarrow Es$



Problems: cross-sections from 100 b → 1 pb, amount from 1000 kg → 1 mg

Prehistory

- **1966: A. Sobiczewski, F.A. Gareev, B.N. Kalinkin: next “magic numbers” are Z=114, N=184;**
- **1966: V.M. Strutinsky; “shell correction” method;**
- **1967: H.B. Meldner: next “magic numbers” are Z=114, N=184.**

Accuracy of predictions:

- **Spontaneous fission half-life: $T_{1/2} * 10^{\pm 10}$!!**
- **α-decay: $T_{1/2} * 10^{\pm 10}$!!**

P. Fowler, Tracks of SHE!?

Synthesis of SHE at accelerators

- **1971; Orsay, France; $^{232}Th + ^{82}Kr \rightarrow ^{310}126 + 4n$; $\sigma_{4n} < 0.5$ mb !!!**
- **1971; Dubna, SU; $^{208}Pb + ^{70}Zn \rightarrow ^{276}112 + 2n$; $\sigma_{2n} < 0.1$ mb !!! (1996, GSI, Germany);**
- **1971-1975; Dubna, SU; deep inelastic or fission reactions of ^{76}Ge, $^{136}Xe + ^{238}U$;**
- **1975; Dubna, SU; ^{48}Ca + actinides:**

  ^{48}Ca-consumtion : 50 – 100 mg/h, 200 US$/mg;

  Total amount: 5 g in SU, 5g in US.

Shell corrections

Proton shell:

114 or/and 126, 120 ?

Neutron shell:

172 or/and 184 ?

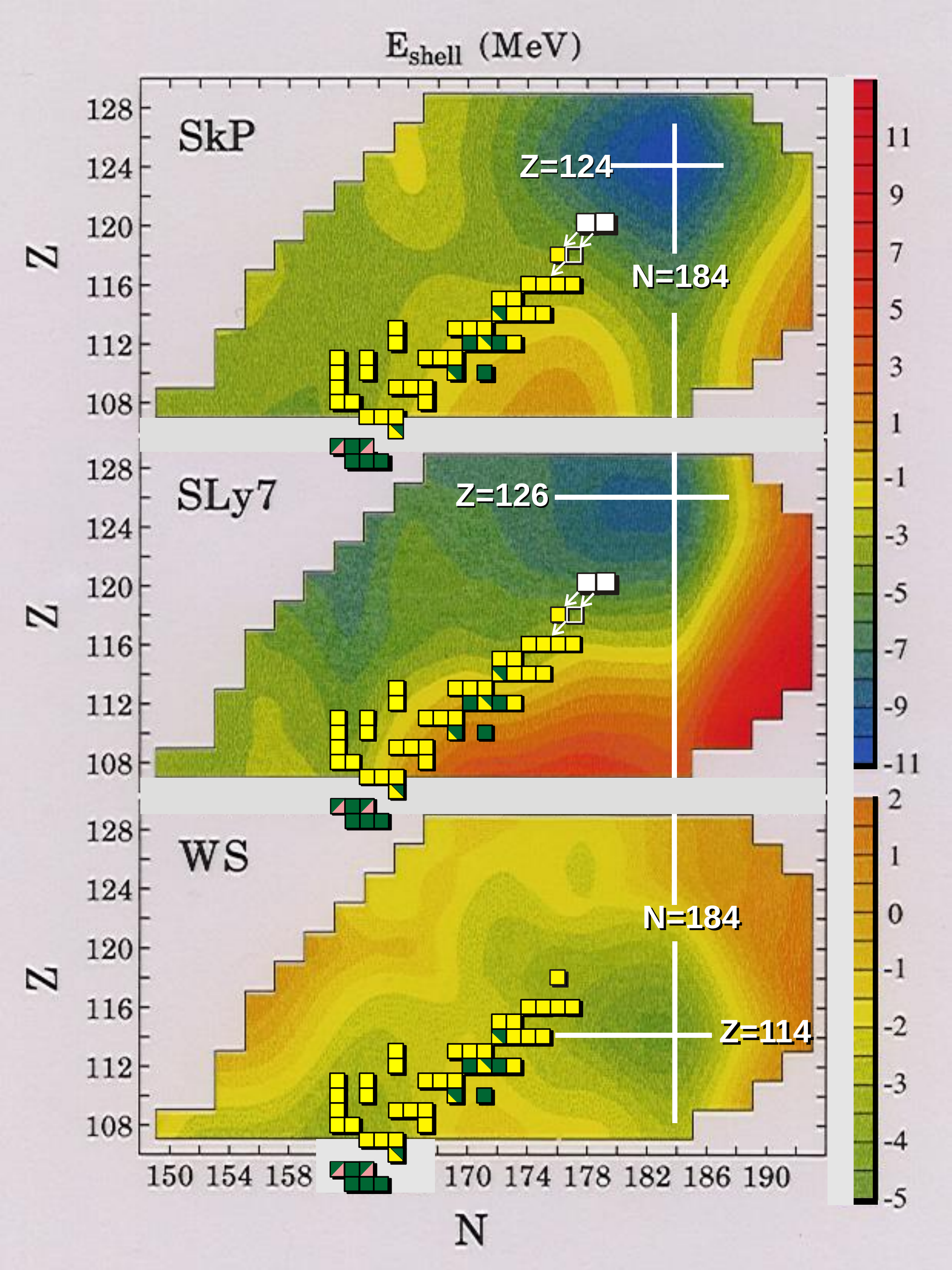
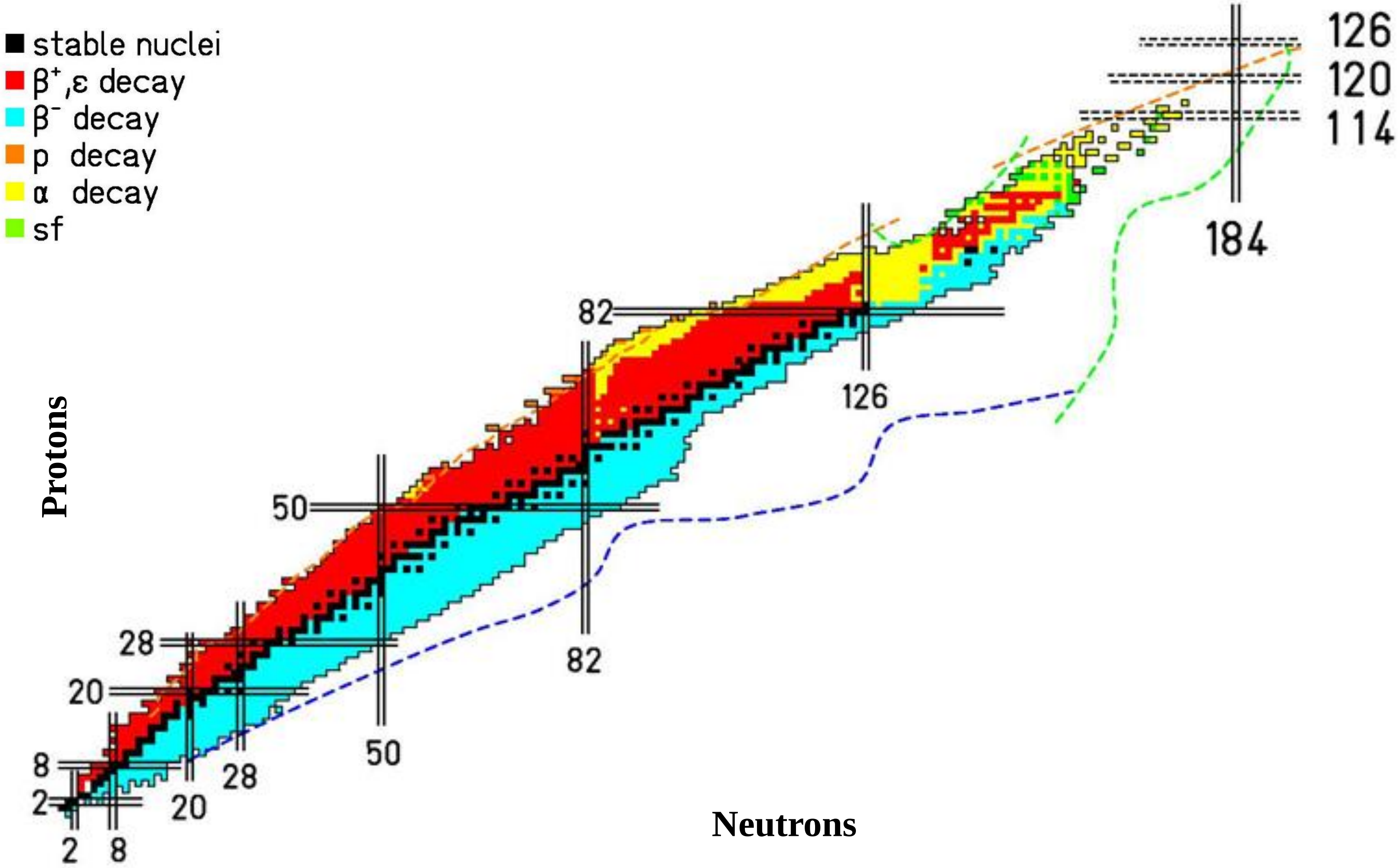
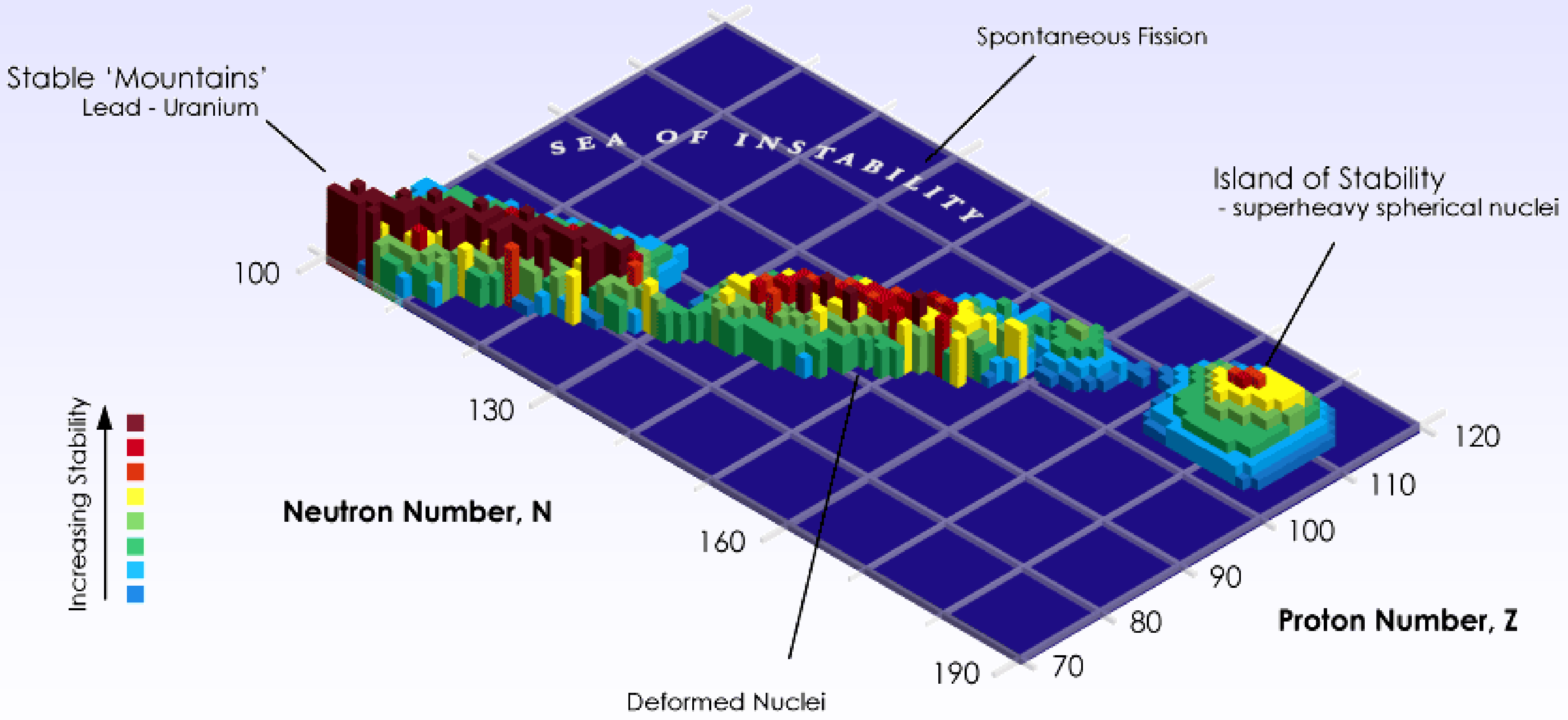


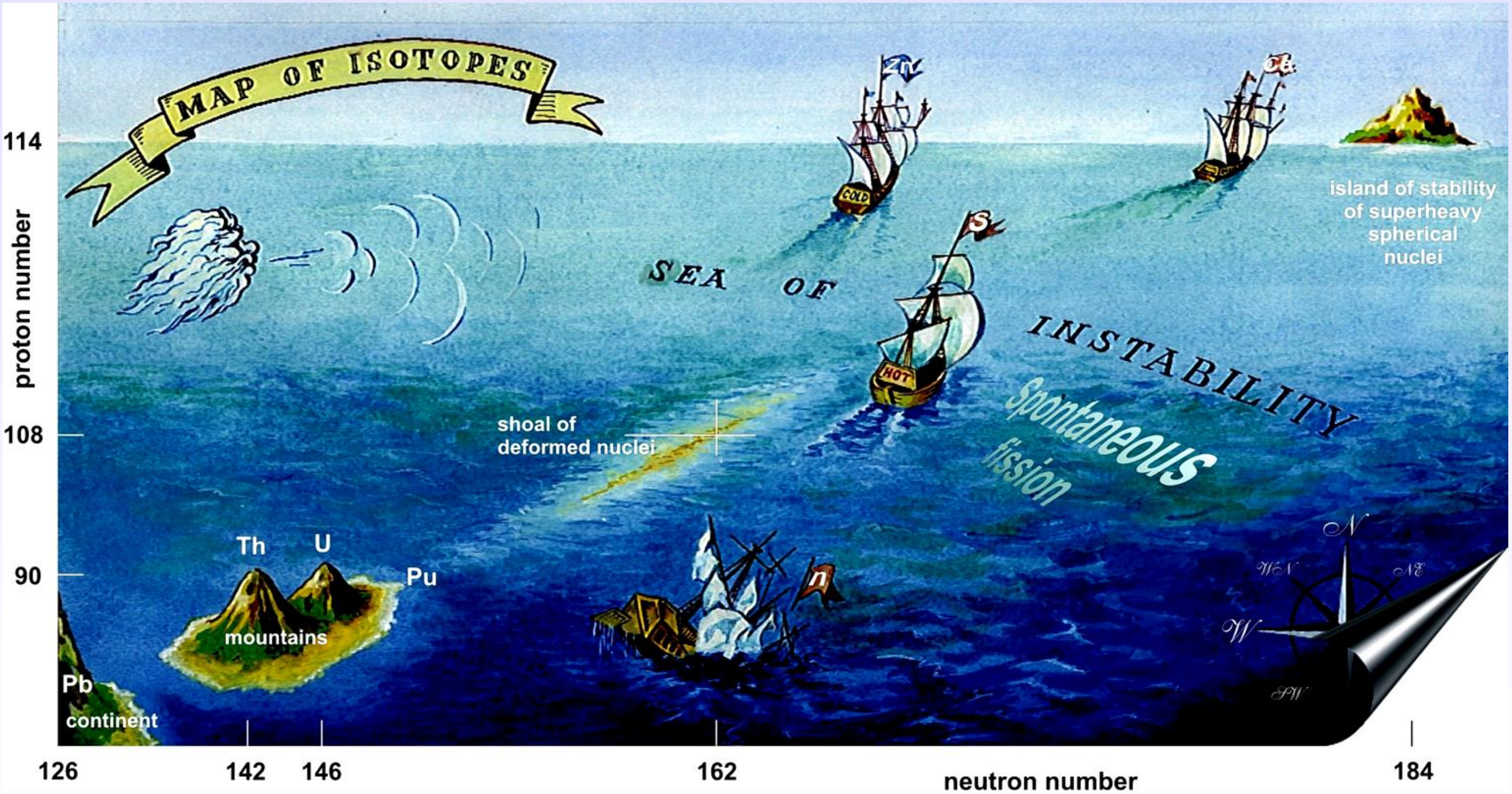
Chart of the Nuclides (decay modes)



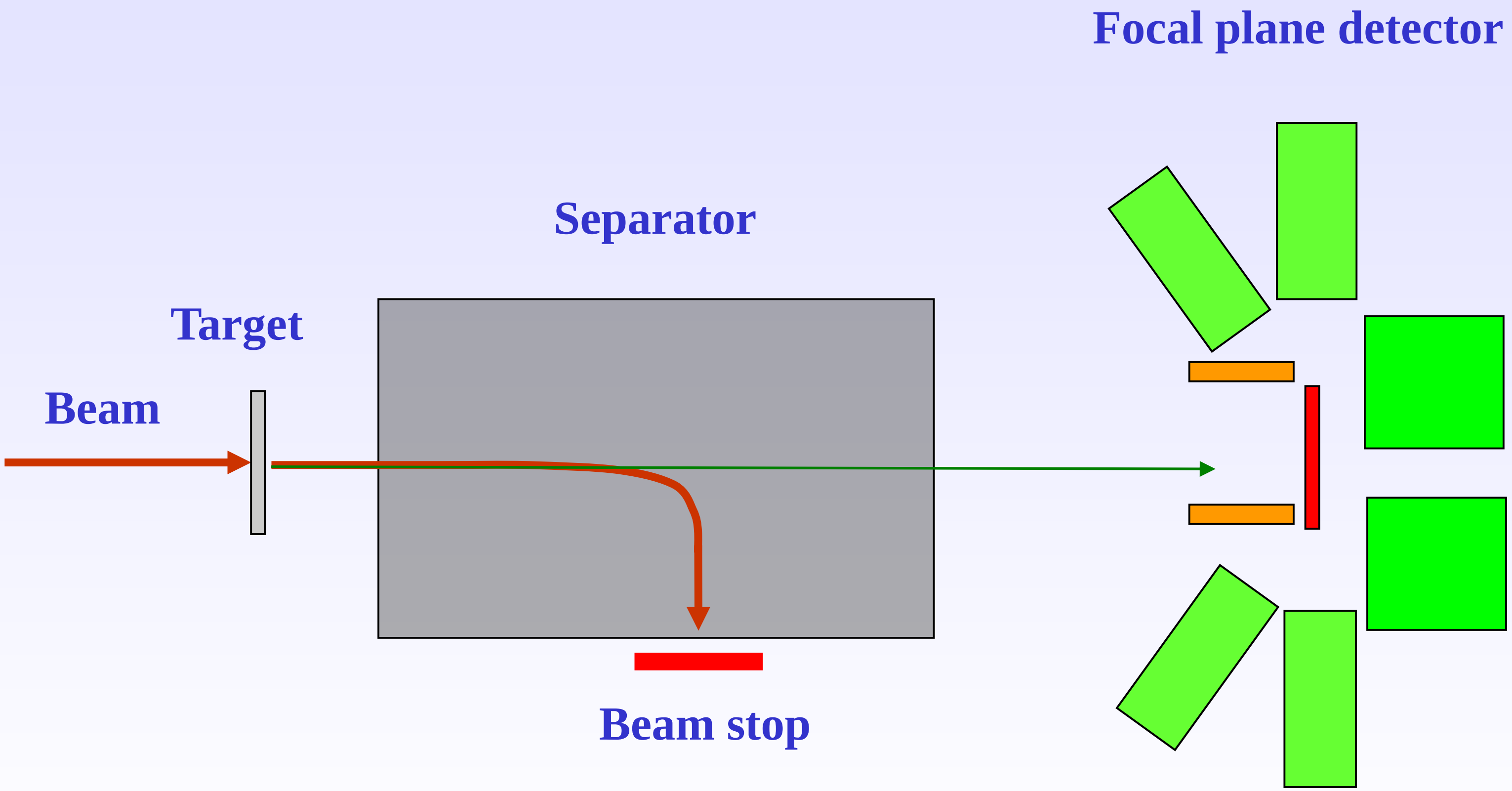
Theoretical predictions of position of SHE



Artistic Chart of the Nuclides

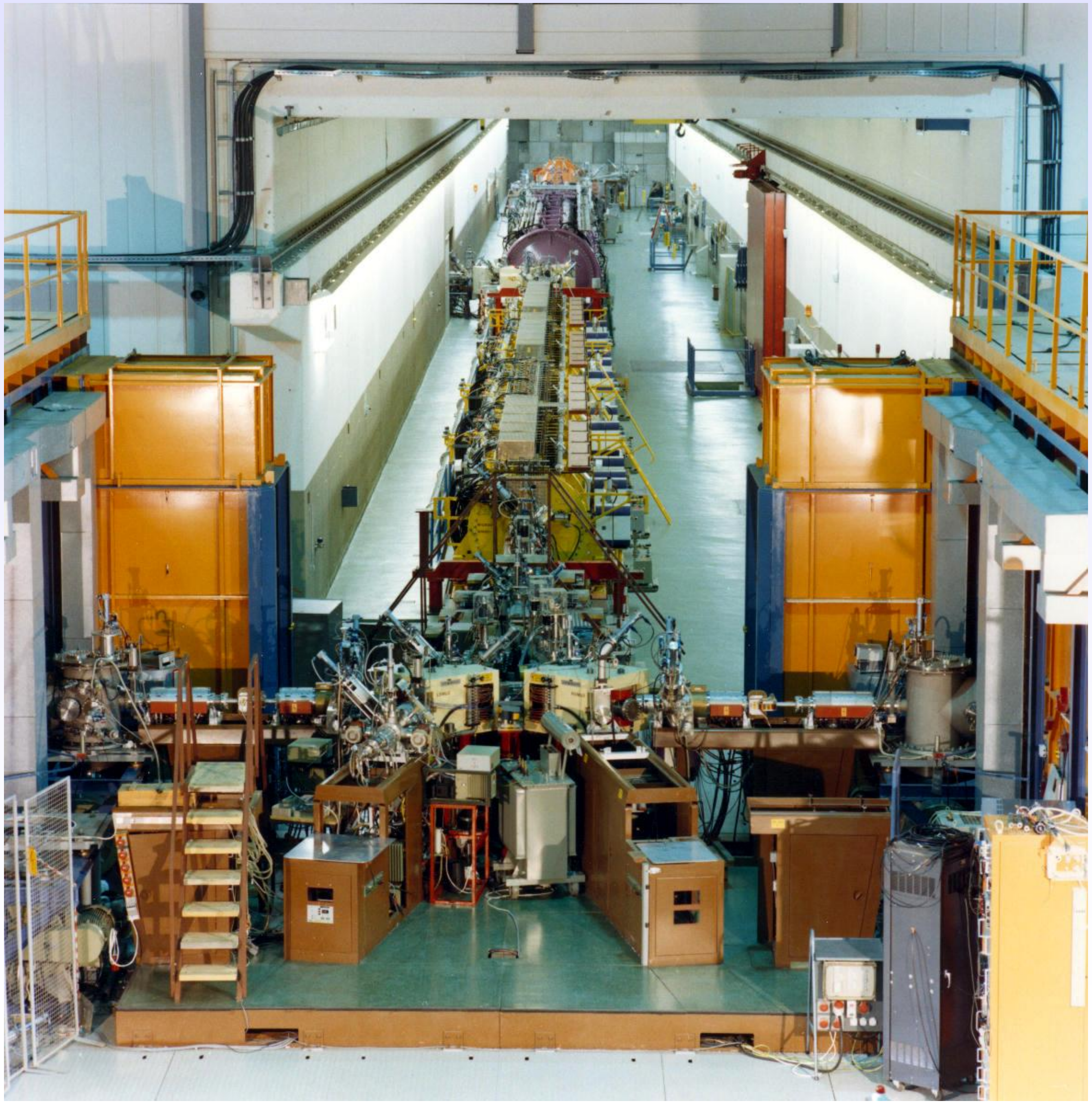


How to synthesize?



FLNR U400 cyclotron

UNILAC (GSI)



Reactions of Synthesis

Act. + ^{48}Ca

Projectiles ^{48}Ca produced by Heavy Ion Accelerator U400;

Energy: 235-250 MeV
(v ≈ 0.1 c);
Intensity: 1.0-1.5 pμA
($n \times 10^{12} \div 10^{13}$ 1/s);
Consumption: 0.5-0.8 mg/h
Beam dose: $(0.3\text{-}3.0) \cdot 10^{19}$

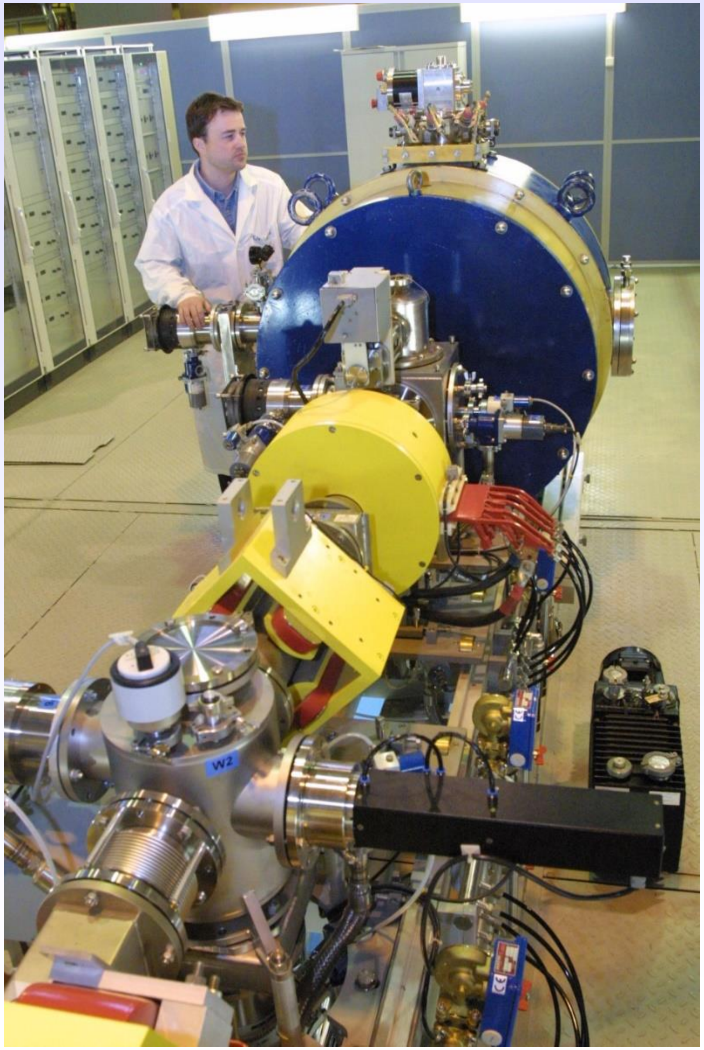
Prices per 1 mg

^{197}Au ≈ 0.045 US$
$^{nat}U_3O_8$ ≈ 0.03 US$
^{239}Pu ≈ 4 US$
^{48}Ca ≈ 80 US$
^{249}Cf ≈ 60,000 US$

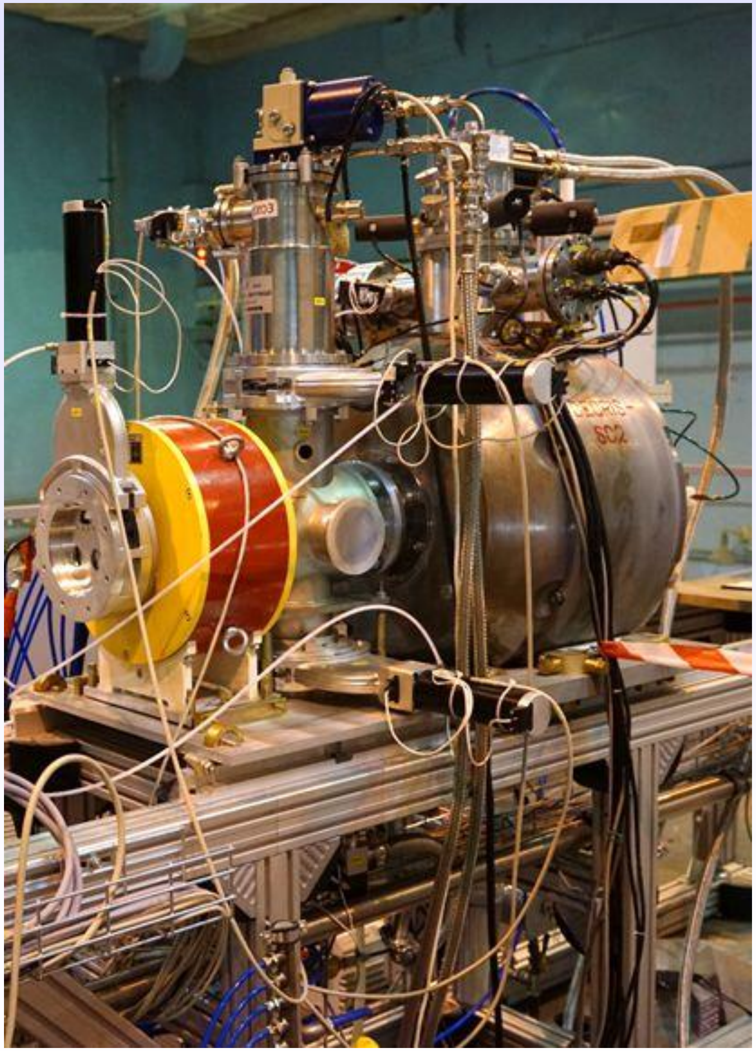
Target materials	Producer	Isotope enrichment (%)
^{232}Th	----	100
^{233}U	RFNC	---
^{238}U	----	99.3
^{237}Np	IAR	99.3
^{239}Pu	RFNC	---
^{240}Pu	IAR/ORNL	99.98
^{242}Pu	RFNC/ORNL	99.98
^{244}Pu	ORNL	98.6
^{243}Am	IAR / ORNL	99.9
^{245}Cm	IAR	98.7
^{248}Cm	IAR /ORNL	97.4
^{249}Bk	ORNL	≥ 95
^{249}Cf	IAR/ORNL	97.3
^{249,250,251}Cf	ORNL	(50+14+36)%

Superconducting 18 GHz ECR ion sources

DECRIS-SC1

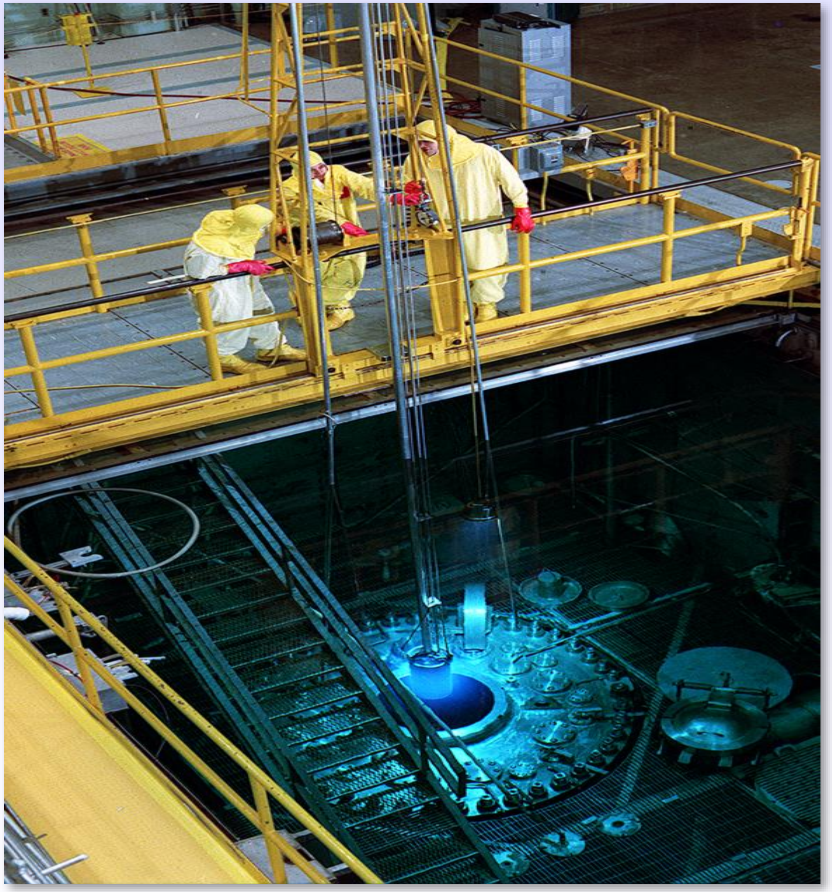


DECRIS-SC2

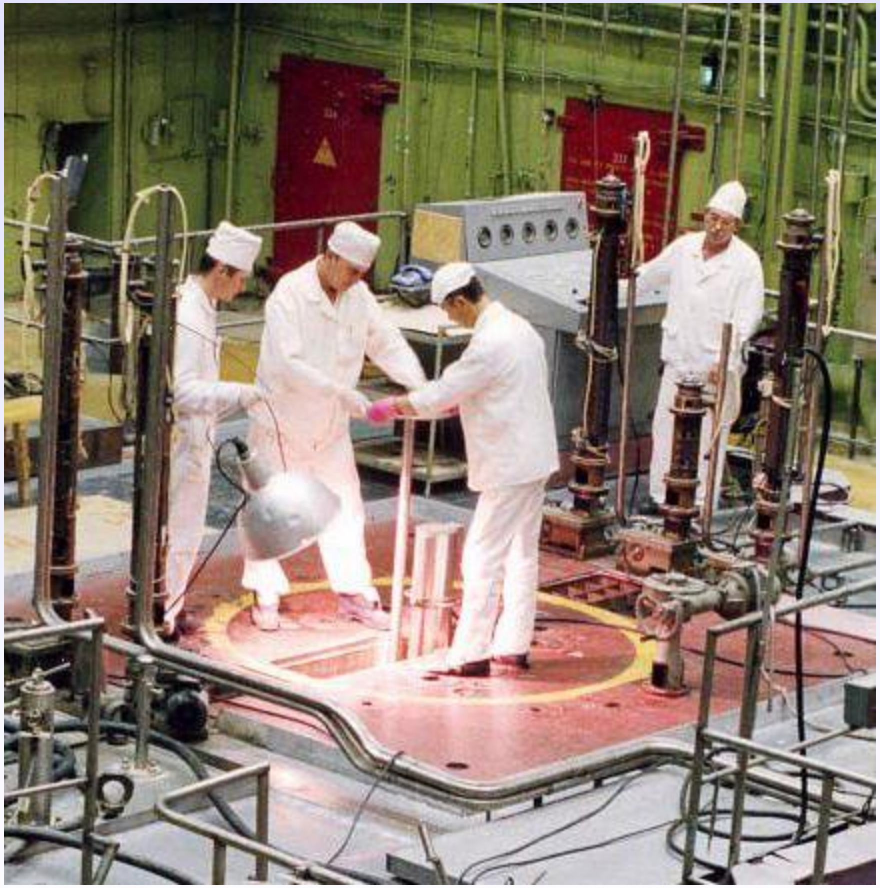


Isotope reactors

HFIR, ORNL, Oak Ridge, USA, 85 MW



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

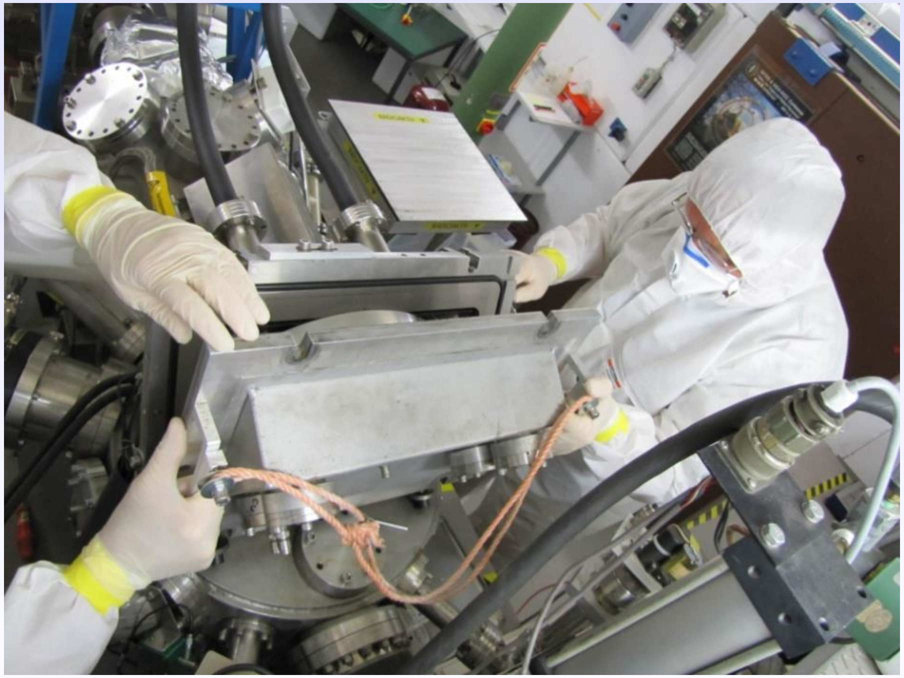


Isotope separator is necessary !

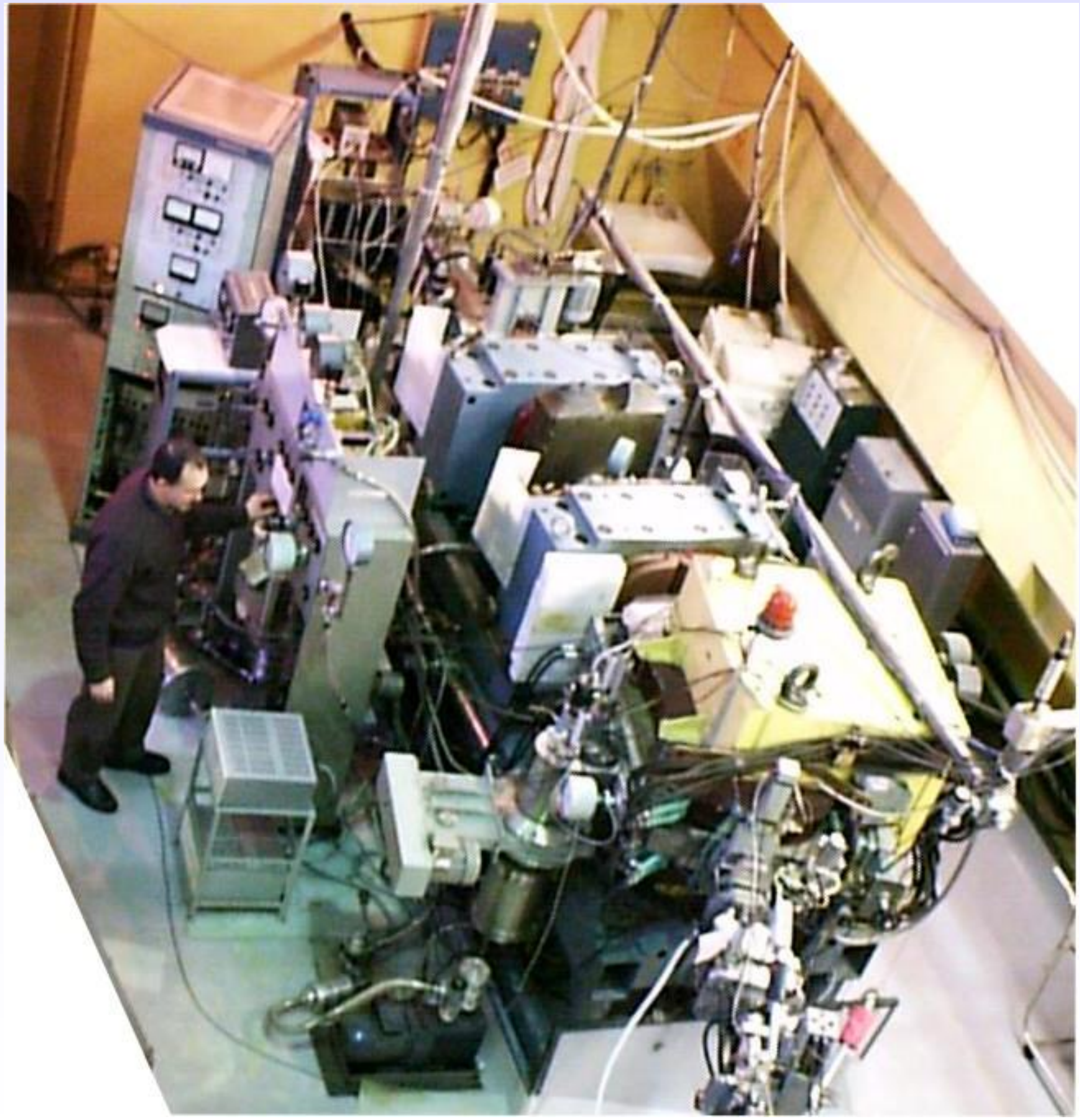
22 mg of ^{249}Bk, ≈ 1 M$, 1 year at HIFR ORNL

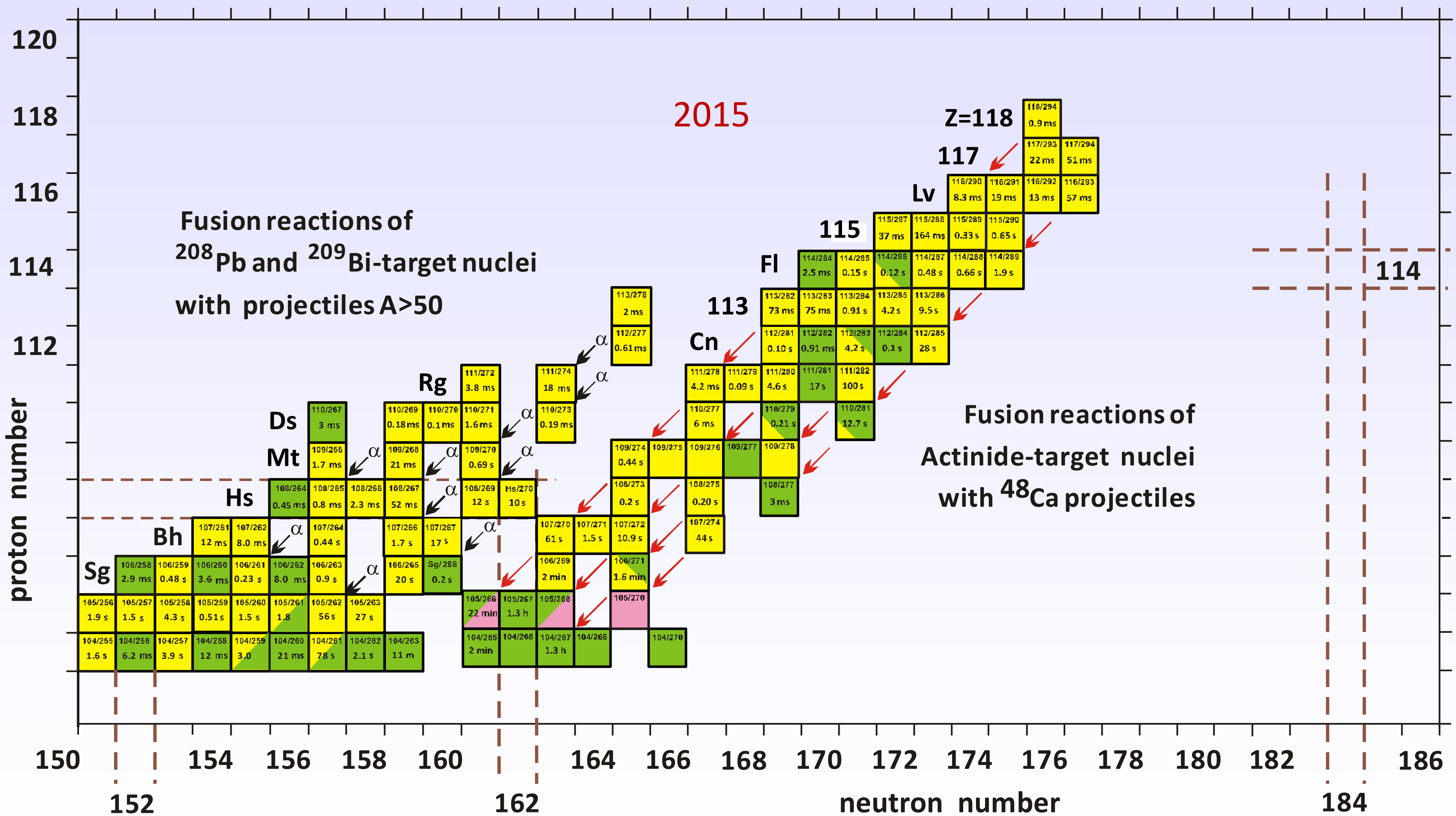
$Bk(NO_3)_3$Product

Targets – radiation safety



Dubna Gas Filled Recoil Separator



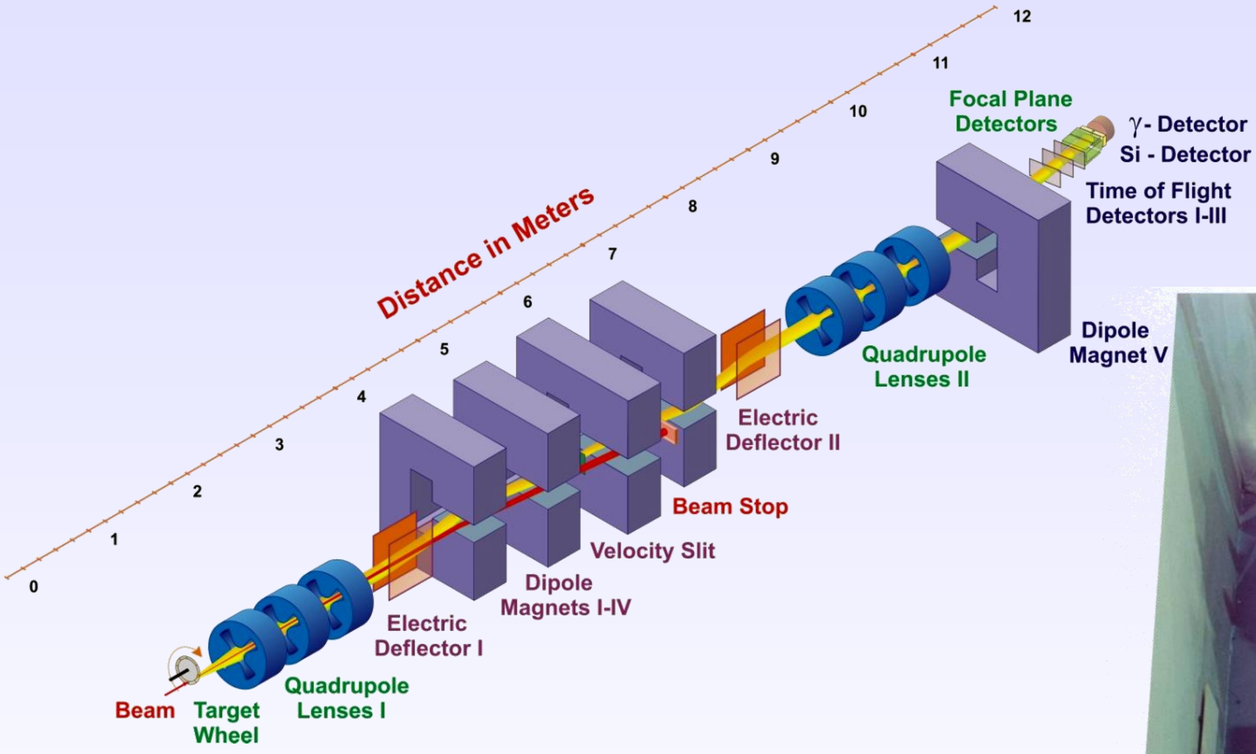

2015
Fusion reactions of
^{208}Pb and ^{209}Bi-target nuclei
with projectiles A>50
Fusion reactions of
Actinide-target nuclei
with ^{48}Ca projectiles
proton number
neutron number
120
118
116
114
112
150
152
154
156
158
160
162
164
166
168
170
172
174
176
178
180
182
184
186
Sg
Bh
Hs
Mt
Ds
Rg
Cn
113
Fl
115
Lv
117
Z=118
118/294 0.9 ms
117/293 22 ms
117/294 51 ms
116/290 8.3 ms
116/291 19 ms
116/292 13 ms
116/293 57 ms
115/287 37 ms
115/288 164 ms
115/289 0.33 s
115/290 0.65 s
114/284 2.5 ms
114/285 0.15 s
114/286 0.12 s
114/287 0.48 s
114/288 0.66 s
114/289 1.9 s
113/278 2 ms
113/282 73 ms
113/283 75 ms
113/284 0.91 s
113/285 4.2 s
113/286 9.5 s
112/277 0.61 ms
112/281 0.10 s
112/282 0.91 ms
112/283 4.2 s
112/284 0.1 s
112/285 28 s
111/272 3.8 ms
111/274 18 ms
111/278 4.2 ms
111/279 0.09 s
111/280 4.6 s
111/281 17 s
111/282 100 s
110/267 3 ms
110/269 0.18 ms
110/270 0.1 ms
110/271 1.6 ms
110/273 0.19 ms
110/277 6 ms
110/279 0.21 s
110/281 12.7 s
109/266 1.7 ms
109/268 21 ms
109/270 0.69 s
109/274 0.44 s
109/275
109/276
109/277
109/278
108/264 0.45 ms
108/265 0.8 ms
108/266 2.3 ms
108/267 52 ms
108/269 12 s
Hs/270 10 s
108/273 0.2 s
108/275 0.20 s
108/277 3 ms
107/261 12 ms
107/262 8.0 ms
107/264 0.44 s
107/266 1.7 s
107/267 17 s
107/270 61 s
107/271 1.5 s
107/272 10.9 s
107/274 44 s
106/258 2.9 ms
106/259 0.48 s
106/260 3.6 ms
106/261 0.23 s
106/262 8.0 ms
106/263 0.9 s
106/265 20 s
Sg/266 0.2 s
106/269 2 min
106/271 1.6 min
105/256 1.9 s
105/257 1.5 s
105/258 4.3 s
105/259 0.51 s
105/260 1.5 s
105/261 1.8
105/262 56 s
105/263 27 s
105/266 22 min
105/267 1.3 h
105/268
105/270
104/255 1.6 s
104/256 6.2 ms
104/257 3.9 s
104/258 12 ms
104/259 3.0
104/260 21 ms
104/261 78 s
104/262 2.1 s
104/263 11 m
104/265 2 min
104/266
104/267 1.3 h
104/268
104/270
α

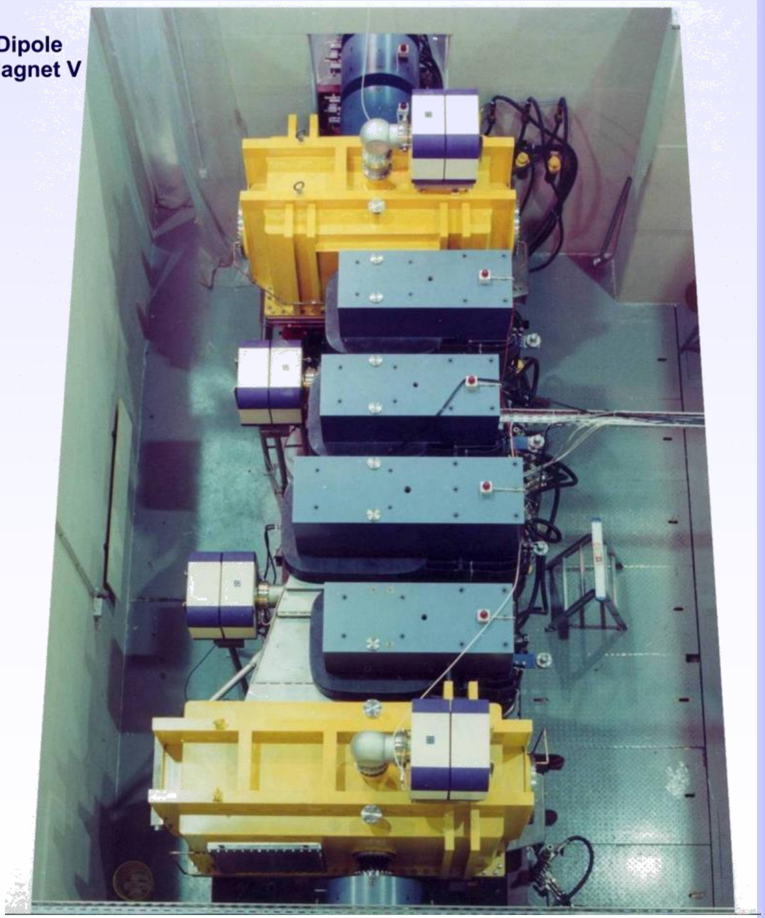
Confirmations

(2007-2014)

A/Z	Setup	Laboratory	Publications
$^{283}112$	SHIP	GSI Darmstadt	Eur. Phys. J. A 32, 251 (2007)
$^{283}112$	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)
$^{294}117$	TASCA	GSI-Mainz	P.R. Lett. 112, 172501 (2014)

The Velocity Filter «SHIP»





TransActiniden Separator und Chemie Apparatur (TASCA) (GSI, Darmstadt)

The Festive Naming Ceremony of the new chemical elements 114 - Flerovium and 116 - Livermorium took place on 24 October 2012 in Moscow

IUPAC President Prof. Kazuyuki Tatsumi

William Goldstein (Livermore), Yuri Oganessian (JINR) and James Roberto (Oak Ridge)

IUPAC

International Union of Pure and Applied Chemistry

30th December 2015:

Discovery of new elements with atomic numbers 115, 117, and 118 is approved!

Priority for elements 115 and 117 is assigned to:

JINR (Dubna) - LLNL (California, USA) - ORNL (Oak Ridge, USA) collaboration.

Priority for element 118 is assigned to:

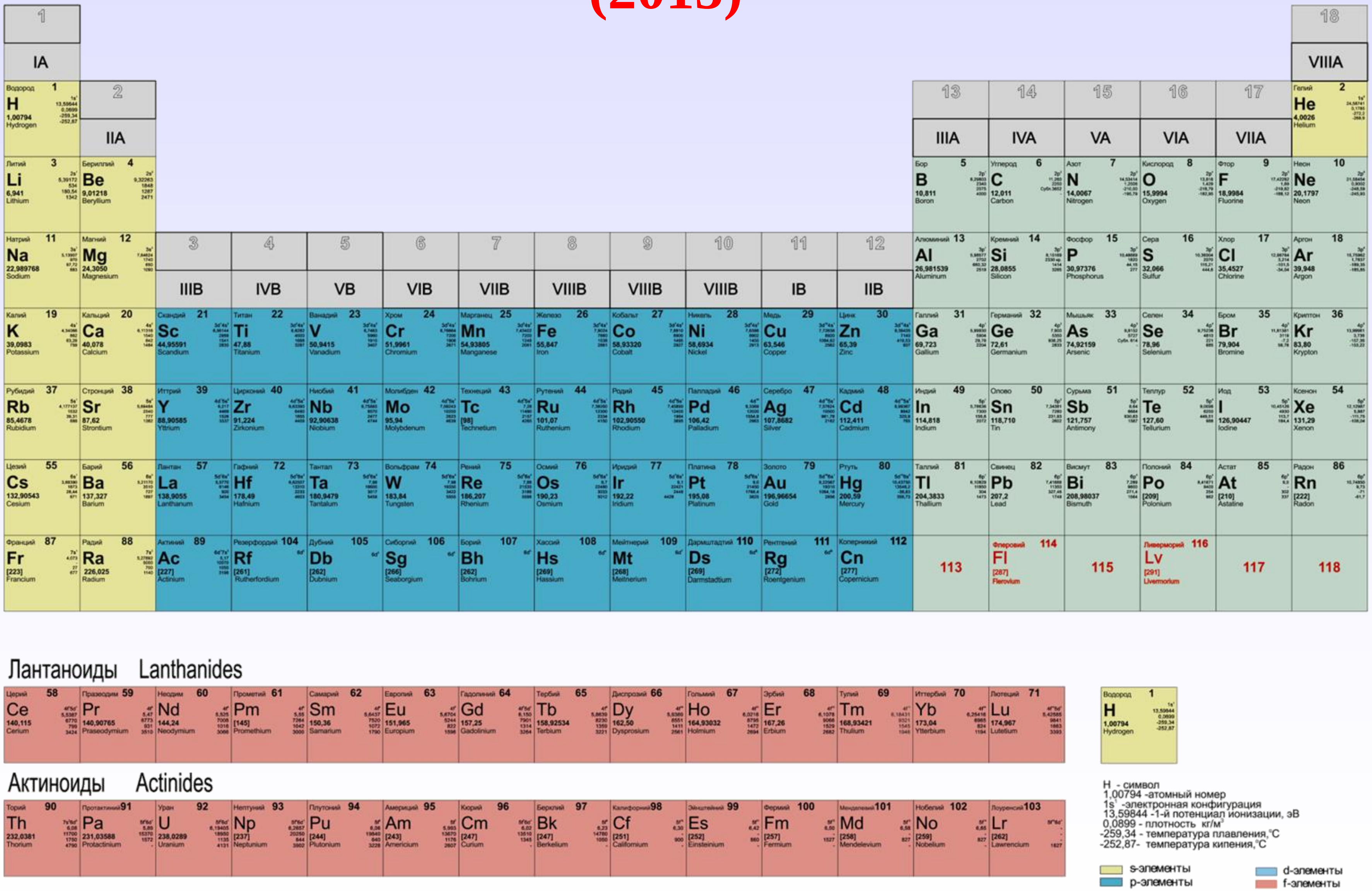
JINR (Dubna) - LLNL (California, USA) collaboration.

The 7th period of the periodic table of elements is now complete!

113	114	115	116	117	118
(Nh)	Fl	(Mc)	Lv	(Ts)	(Og)
(Nihonium)	Flerovium	(Moscovium)	Livermorium	(Tenessine)	(Oganesson)

All the elements were synthesized for the first time at the U400 cyclotron of the Flerov Laboratory of Nuclear Reactions of JINR.

D.I. Mendeleev's Periodic Table of the Elements (2015)

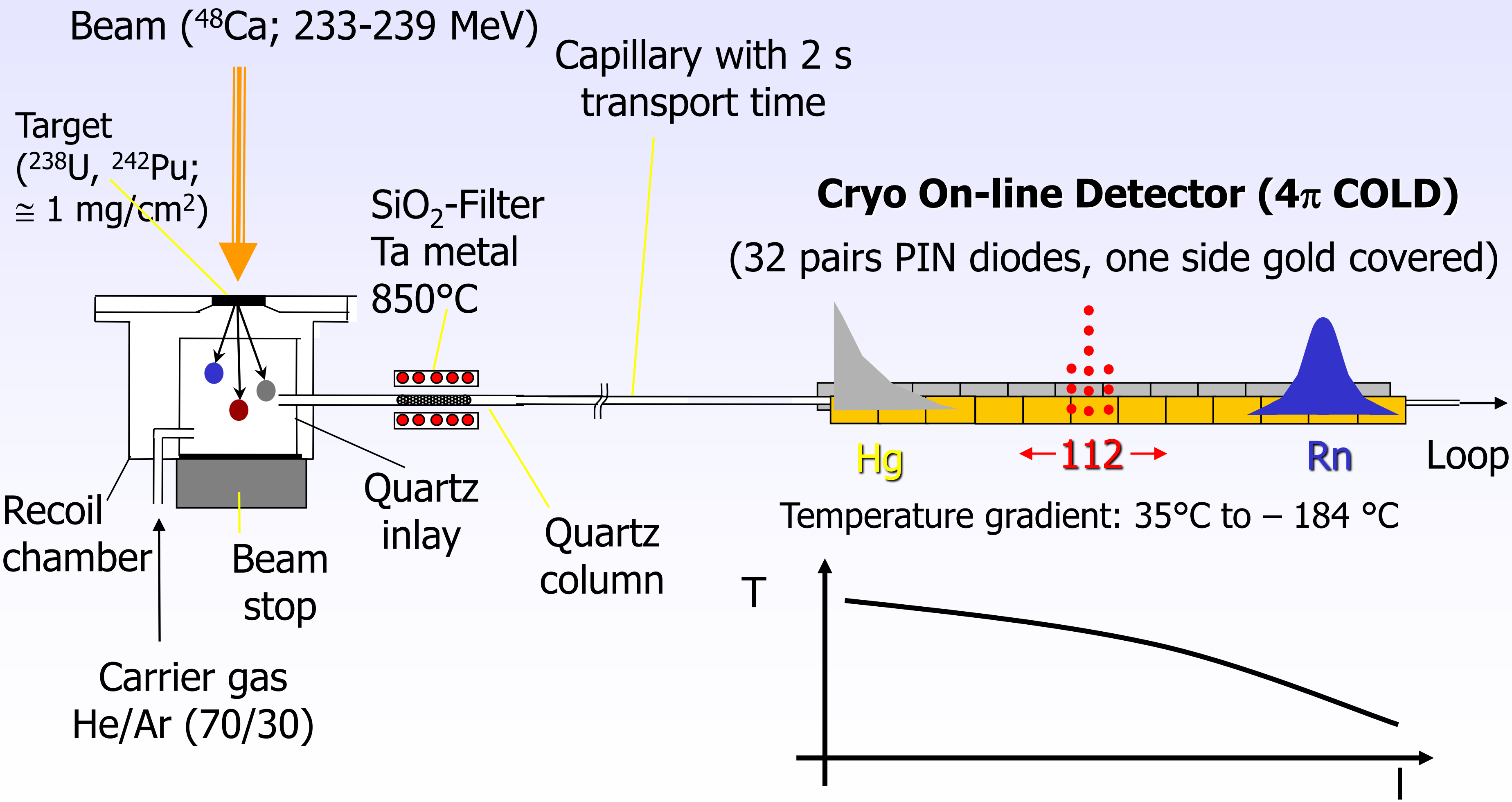


GAS PHASE CHEMISTRY WITH ELEMENTS 112 AND 114

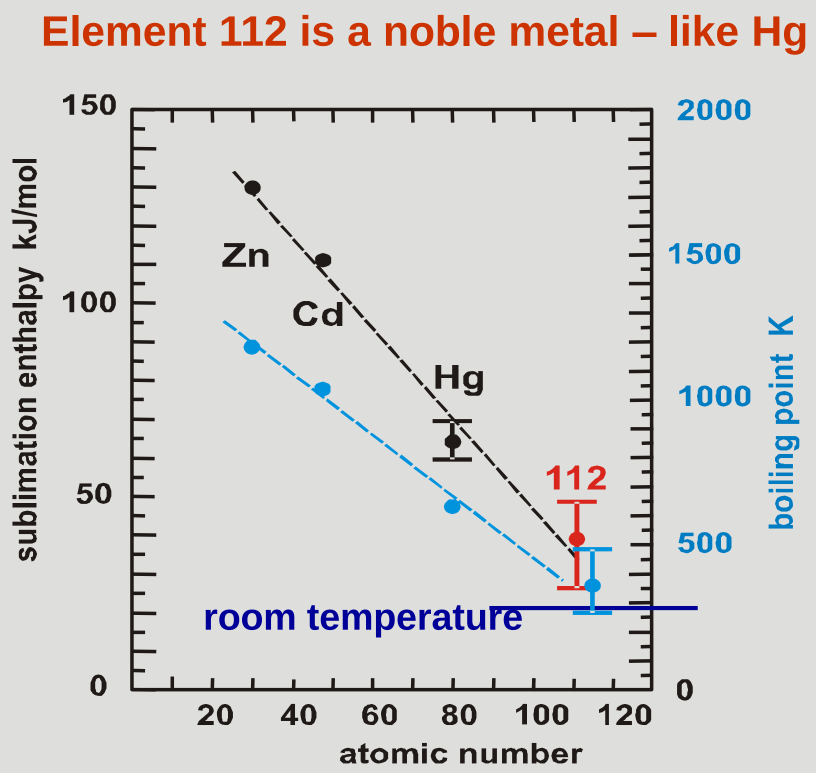
- Are elements 112 and 114 volatile metals?

- How do relativistic effects influence the chemistry of E112 and of E114?

Химия элементов 112 & 114



Trend of sublimation enthalpy within group 12



As predicted by Bernd Eichler, 1974 (!)

That we have learnt:

- SHE can be synthesized;
- Chemistry of SHE can be studied;
- We have only 12,000 hours beam time / year;
- We need new facilities;
- We have not enough experimental space;
- We can not accelerate ions heavier than Xe;
- Radiation safety requirements are strong;

What to do further?
Complete fusion reactions:

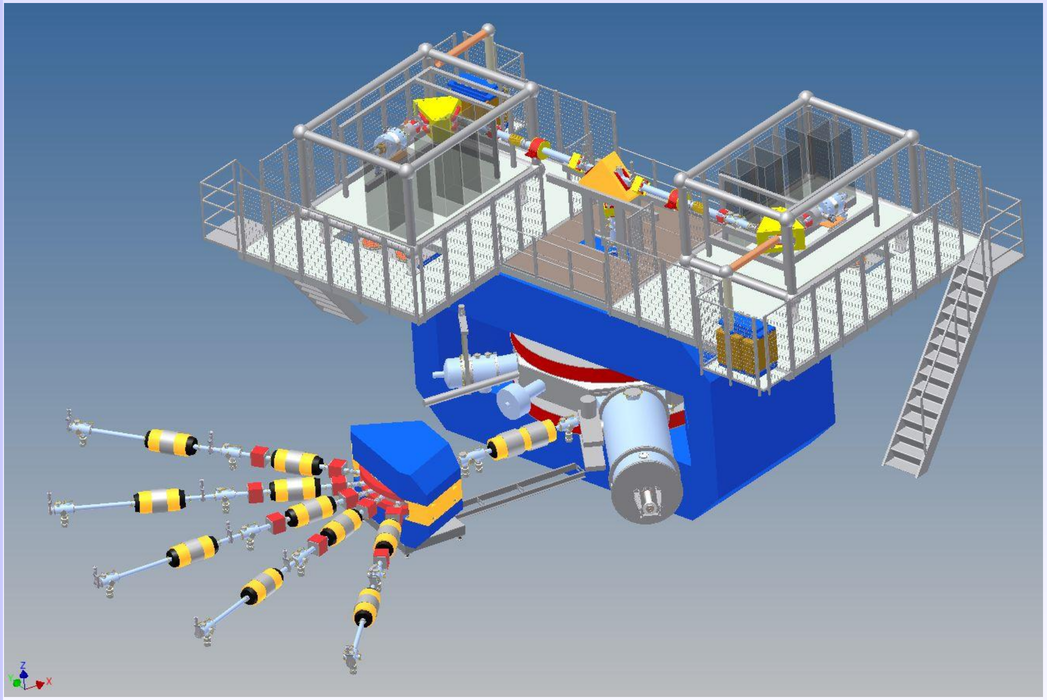
- Higher beam current;
- More target material: 15 mg → 150 mg;

Heaviest target: $^{249}Cf \rightarrow Z_{max} = 118$

↓

- Heavier projectiles (^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni …)
- Heavier targets: ^{250}Cm, ^{251}Cf;
- Exotic targets: ^{254}Es, ^{257}Fm -???;
- Symmetric reactions:
  $^{136}Xe+^{136}Xe$, $^{136}Xe+^{150}Nd$, $^{150}Nd+^{150}Nd$;
- Reactions with RI.

DC280-cyclotron – stand-alone SHE-factory



- Synthesis and study of properties of superheavy elements.
- Search for new reactions for SHE-synthesis.
- Chemistry of new elements.

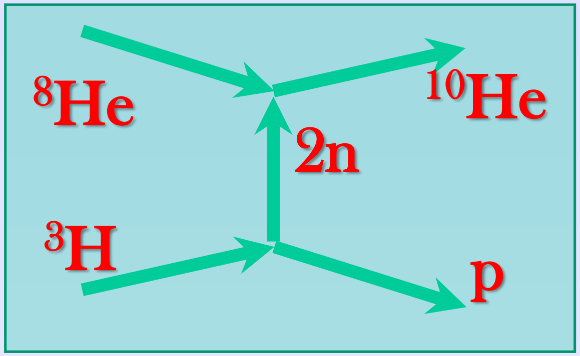
DC280 (expected) E=4÷8 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	$0{,}6\text{-}1{,}2\times10^{14}$
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{124}Sn	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

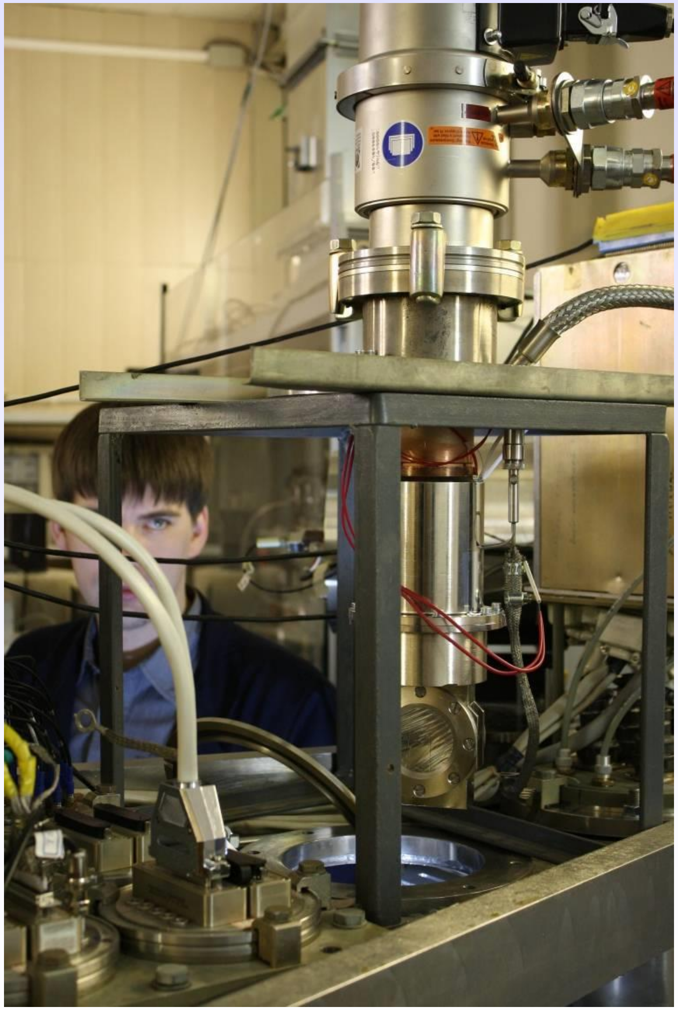
Specialized high-current cyclotron DC280

SHE-Factory (June, 2016)

http://inflnr.jinr.ru/dc280.html

^{10}He: 2n-transfer





Fragment-separator ACCULINNA-2: assembling and testing

Radiation-physical and radioisotope investigations

detailed study of effects induced by heavy ions in matter aimed at applications of beams of accelerated ions in nanotechnology,

investigation of radiation resistance of materials under the influence of multi-charged ions,

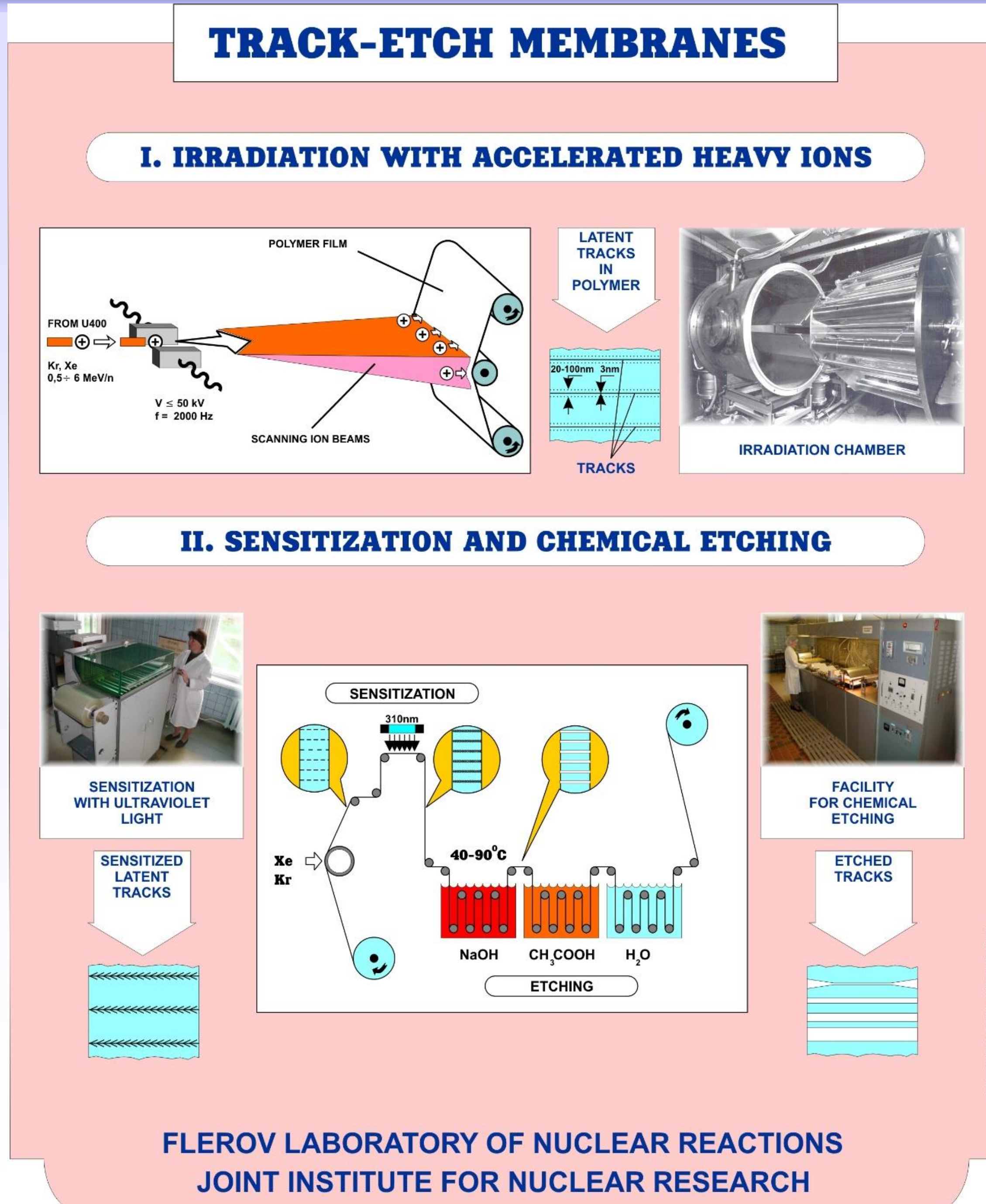
testing of microelectronic circuits for space technology,

development of next-generation of functional track membranes,

synthesis of nano-objects with unique properties for new applications,

development of hybrid nanotechnologies, combining methods of ion track technology and coating, thin-layer, and surface modification technologies,

production of radioisotopes for nuclear medicine and radioecological studies with γ-quanta, α-particle-, and heavy-ion beams;


TRACK-ETCH MEMBRANES
I. IRRADIATION WITH ACCELERATED HEAVY IONS
POLYMER FILM
FROM U400
Kr, Xe
0,5÷ 6 MeV/n
V ≤ 50 kV
f = 2000 Hz
SCANNING ION BEAMS
LATENT TRACKS IN POLYMER
20-100nm
3nm
TRACKS
IRRADIATION CHAMBER
II. SENSITIZATION AND CHEMICAL ETCHING
SENSITIZATION WITH ULTRAVIOLET LIGHT
SENSITIZED LATENT TRACKS
SENSITIZATION
310nm
Xe
Kr
40-90°C
NaOH
CH3COOH
H2O
ETCHING
FACILITY FOR CHEMICAL ETCHING
ETCHED TRACKS
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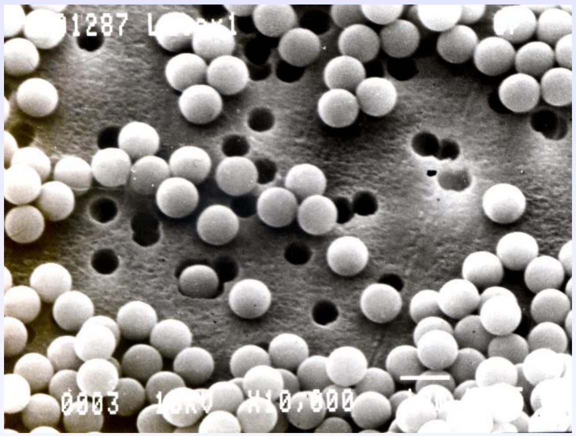
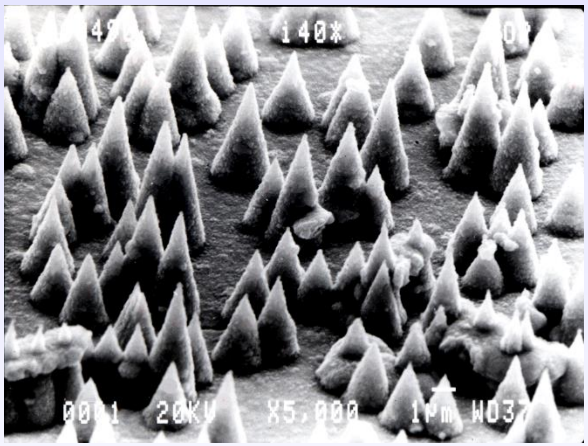
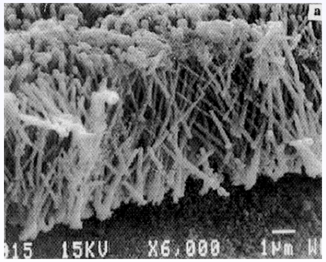
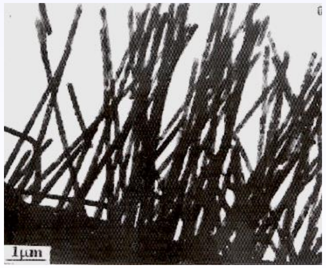
FLEROV LABORATORY OF NUCLEAR REACTIONS
JOINT INSTITUTE FOR NUCLEAR RESEARCH

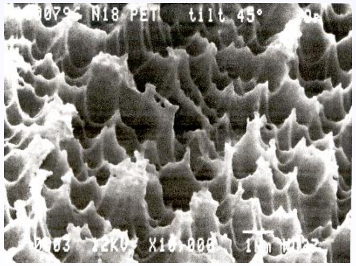
Nano-structures

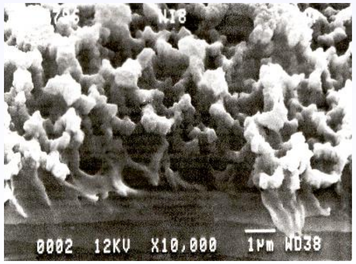












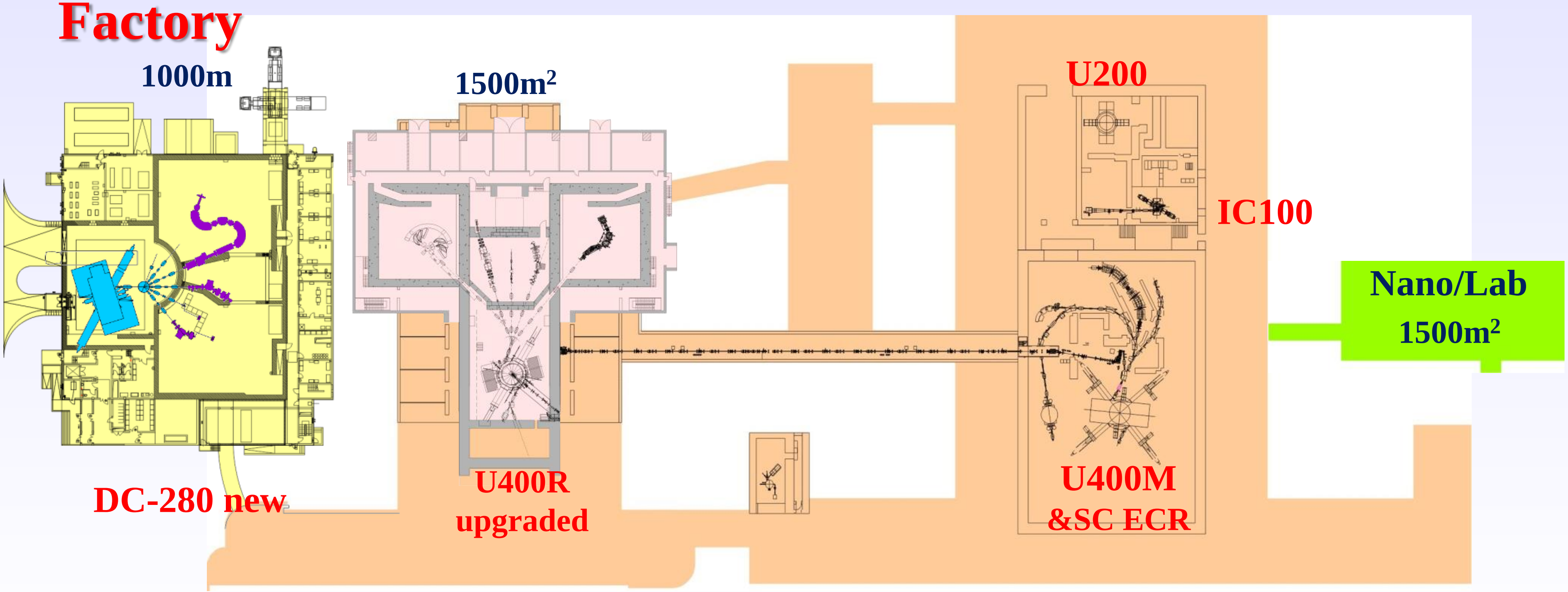
New research instruments (the Nanotechnology Centre)

- Two scanning electron microscopes (Hitachi SU8020 and SU3400) with a number of options (microanalysis, catodoluminescence, etc)
- Specialized equipment for sample preparation for SEM
- Atomic force microscopy with various optical options
- X Ray photoelectron spectroscopy (K-Alpha instrument)
- Fourier-transform IR spectrophotometer
- UV-Vis spectrophotometers
- Specialized electronics for measurements on single nanopores: Axopatch 200B
- Capillary flow porometer and other equipment for membrane testing
- Versatile equipment for chemical lab, etc.

General view of the new laboratory building (Centre of Nanotechnology)

Centre of Nanotechnology, interior view

Full-scale realization off the DRIBs-III -project



Heavy & Super heavy | **Nuclear spectroscopy** | **Light exotic nuclei & Applied research**


THANK YOU
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