Alexander Karpov
FLNR, JINR

Superheavy elements research at Dubna: achievements and perspectives

JINR
114 Flerovium
FLNR
Dubna

DRIBS-III ACCELERATOR COMPLEX

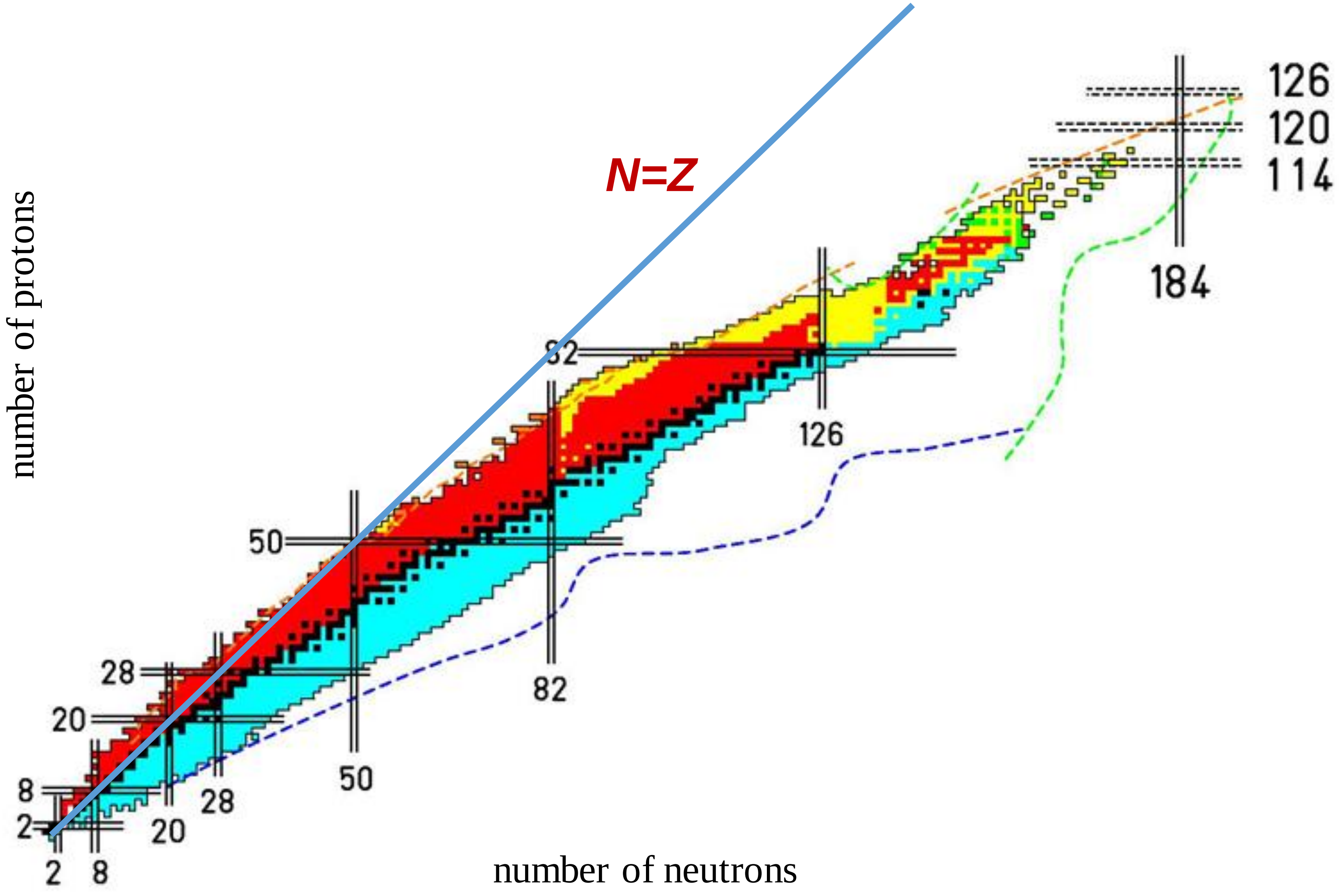
FLEROV LABORATORY OF NUCLEAR REACTIONS

FLNR's basic directions of research:

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

Chart of nuclei

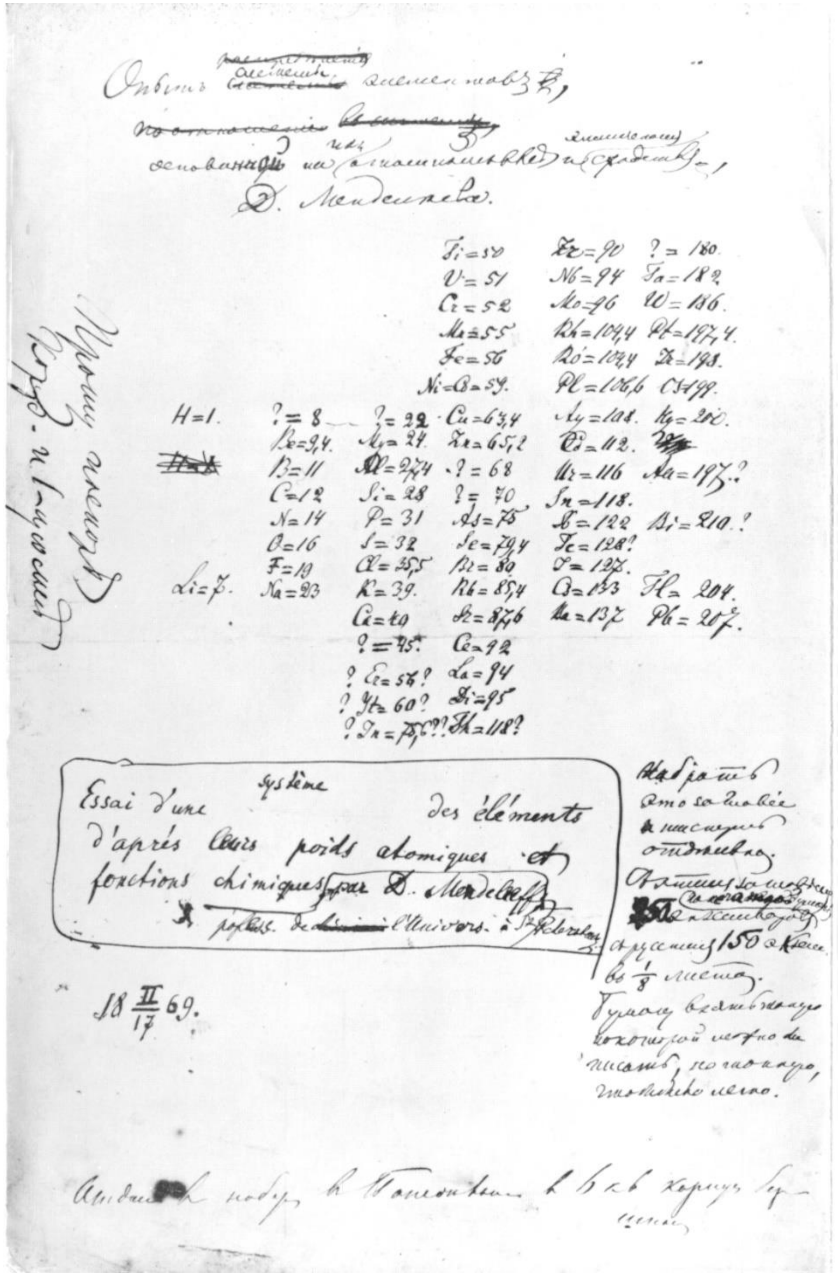
- stable
- beta-minus (β^-)
- beta-plus (β^+)
- alpha decay (α)
- spontaneous fission

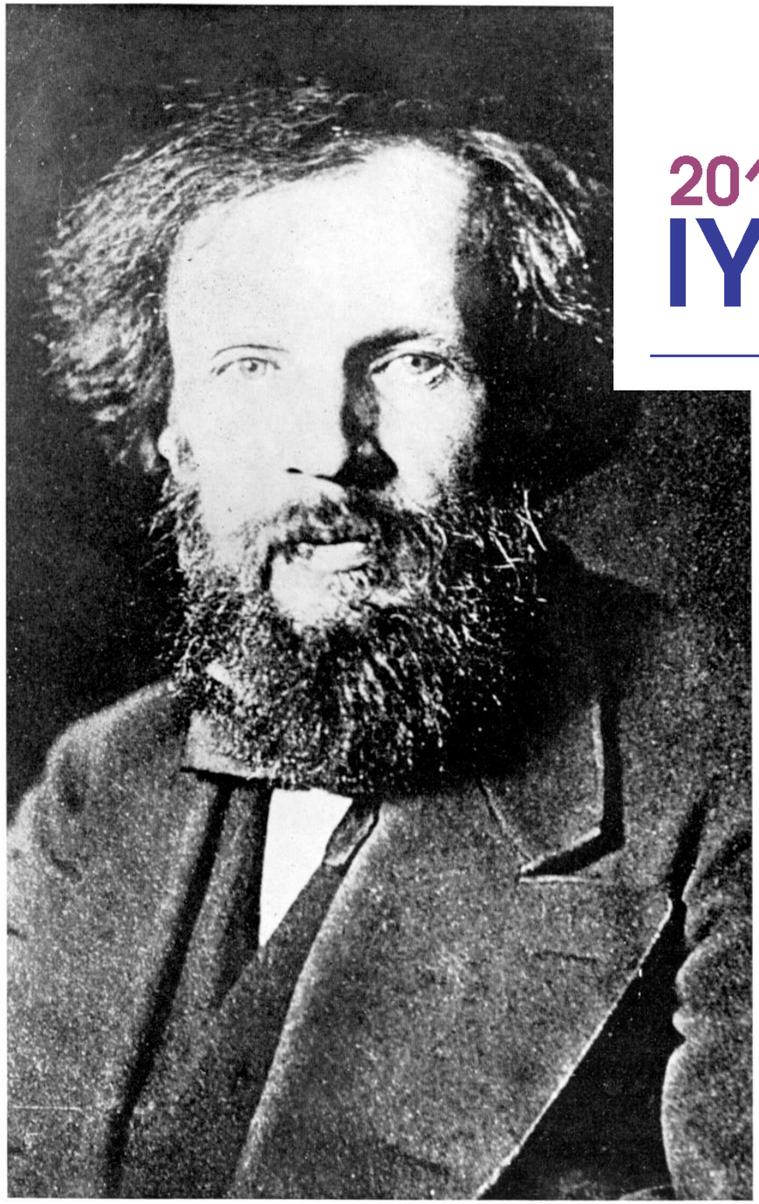


Mendeleev's Table (1869)

International Year
of the Periodic Table of Chemical Elements

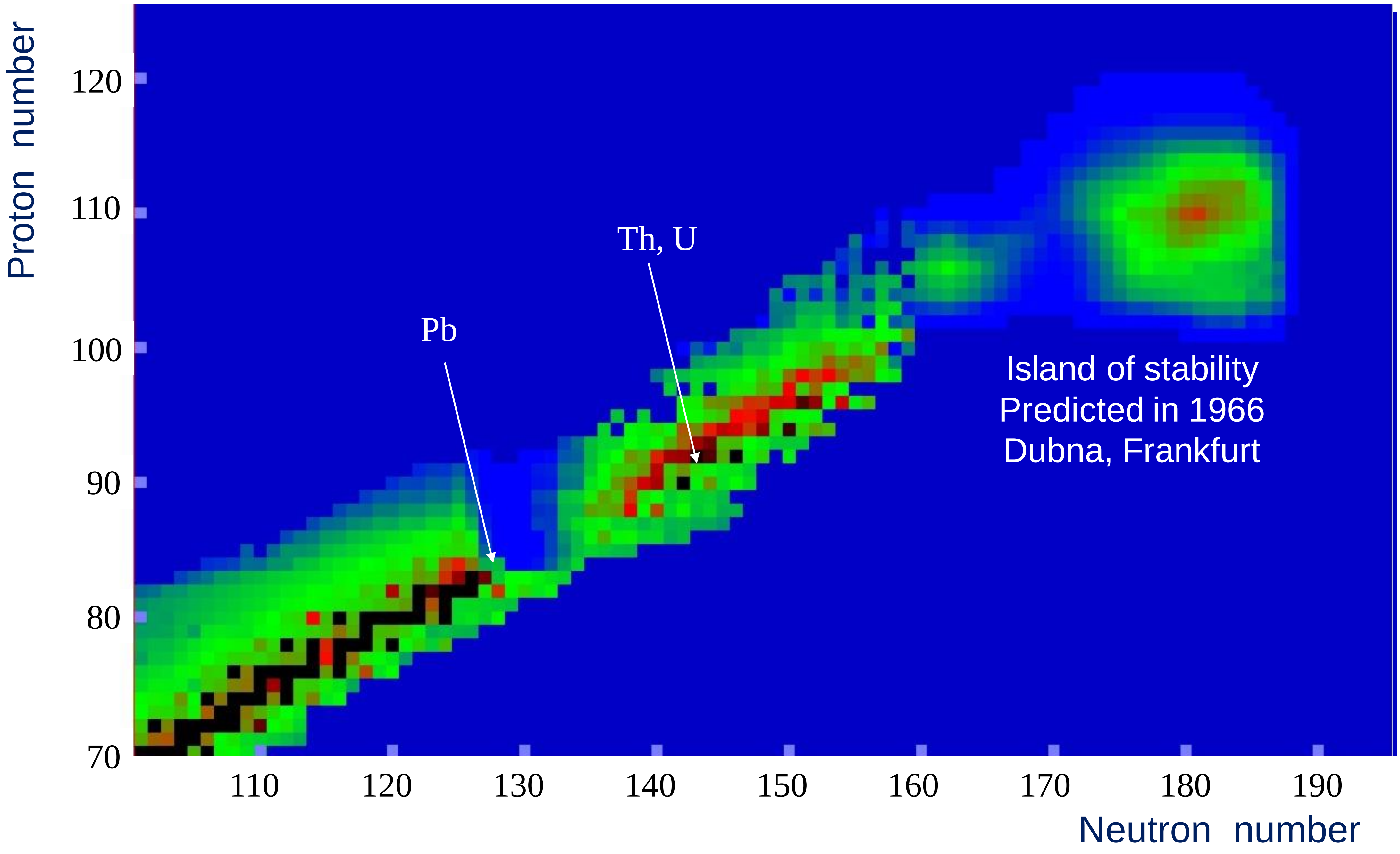
2019 IYPT





Mendeleev’s Table Today

Chart of Nuclei



Synthesis of SHE with accelerators

- 1971; Orce, France:

  $^{232}Th + ^{82}Kr \rightarrow ^{310}126 + 4n; \sigma_{4n} < 0.5$ mb !!!

- 1971; Dubna: $^{208}Pb + ^{70}Zn \rightarrow ^{276}112 + 2n; \sigma_{2n} < 0.1$ mb !!! (1996, GSI, Germany);

- 1971-1975; Dubna: ^{76}Ge, $^{136}Xe + ^{238}U$;

- 1975; Dubna: ^{48}Ca + Actinides:

Los Alamos (USA)

Berkeley (USA)

Dubna (JINR)

Oak Ridge (USA)

Mainz (Germany)

Darmstadt (Germany)

Orsay (France)

Würenlingen (Switzerland)

Tokyo (Japan) some later

Commissioned:	1978
Modernized:	1996
Reconstruction:	2020-2023 (plan)

Tasks:

Stand-alone mode:
- Synthesis of superheavy elements (SHE)
- Chemistry of SHE
- Nuclear & laser spectroscopy
- Nuclear reactions: fusion, fusion-fission & quasi-fission, multi-nucleon transfer reactions
- Applied research

Post-accelerator mode:
- Reactions with exotic nuclei
- Structure of light exotic nuclei

U-400 ACCELERATOR COMPLEX

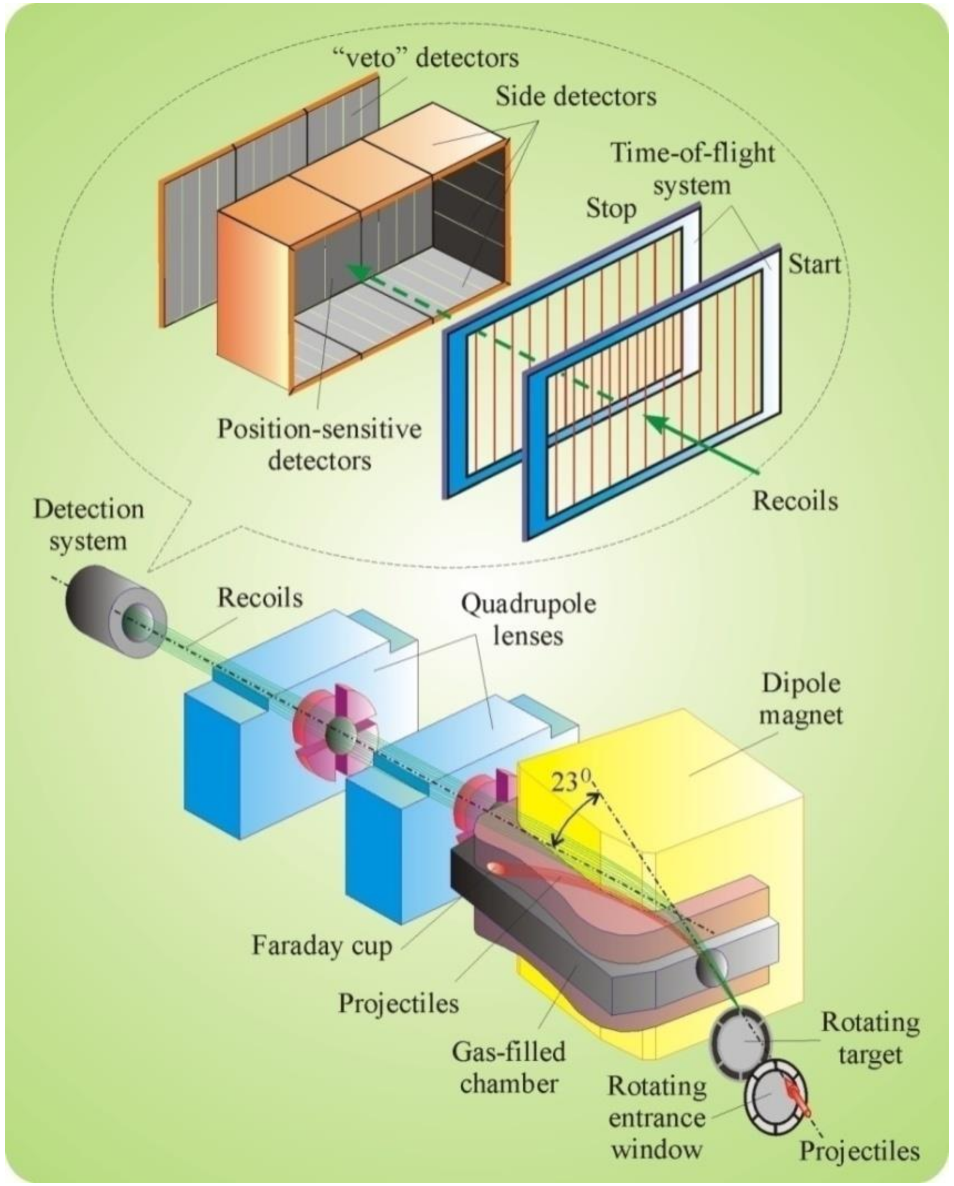
NUCLEAR SPECTROSCOPY AND REACTION MECHANISMS

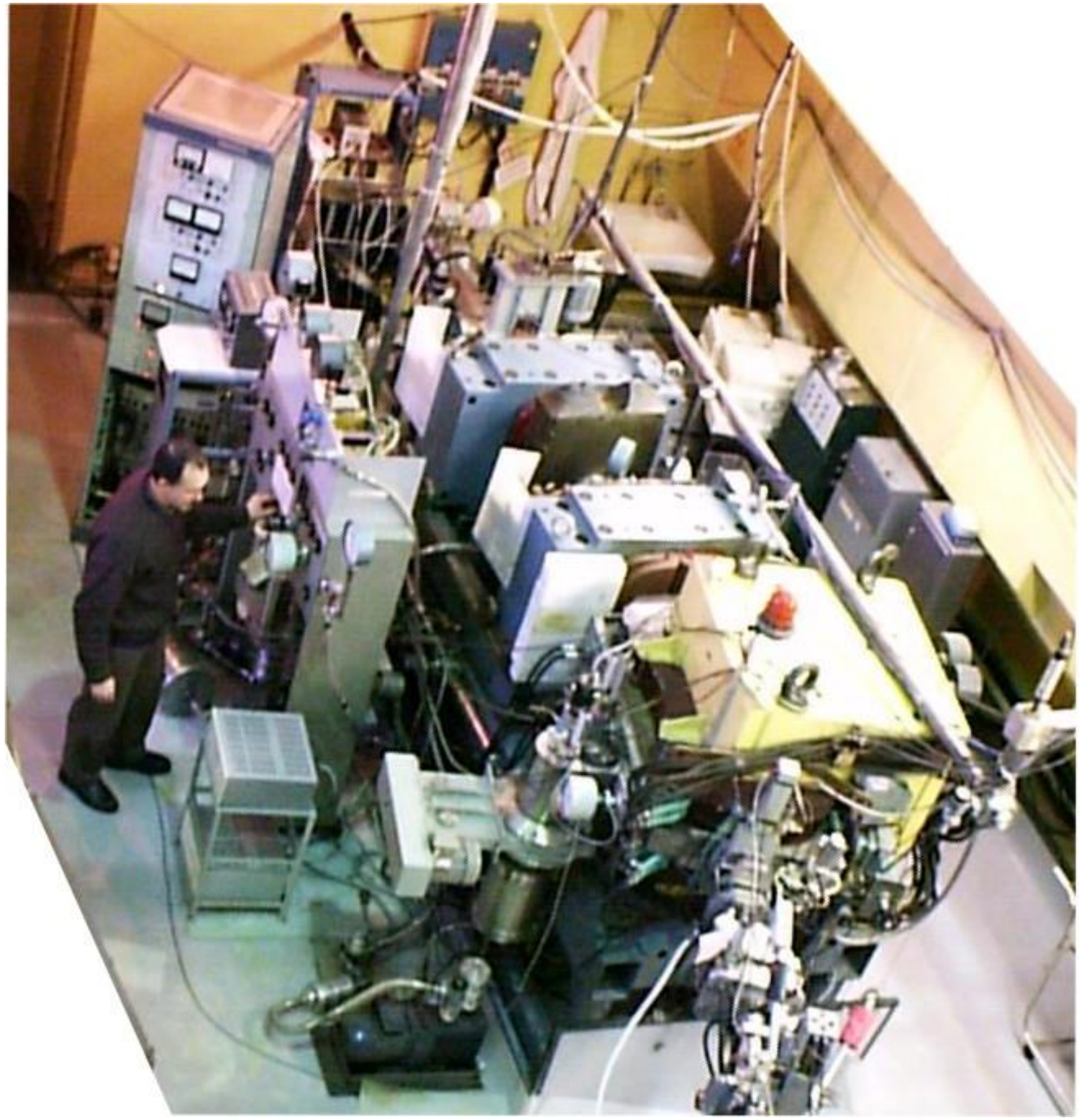
Ion	Ion energies [MeV/A]	Output intensity [pps]
$^{16}O^{2+}$	5.7; 7.9	3×10^{13}
$^{18}O^{3+}$	7.8; 10.5; 15.8	2.6×10^{13}
$^{40}Ar^{4+}$	3.8; 5.1	1×10^{13}
$^{48}Ca^{5+}$	3.7; 5.3	7.2×10^{12}
$^{48}Ca^{9+}$	8.9; 11; 17.7	6×10^{12}
$^{50}Ti^{5+}$	3.6; 5.1	2.4×10^{12}
$^{58}Fe^{6+}$	3.8; 5.4	4.2×10^{12}
$^{84}Kr^{8+}$	3.1; 4.4	1.8×10^{12}
$^{136}Xe^{14+}$	3.3; 4.6; 6.9	4.8×10^{11}
$^{160}Gd^{19+}$	5.5	6×10^{10}
$^{209}Bi^{19+}$	3.4	6×10^{10}

Main parameters	
Energy range	3÷21 MeV/A
K factor max.	650
Pole diameter	4 m
Magnet weight	2100 t
Magnet power	850 kW
Vacuum	10^{-7} Torr

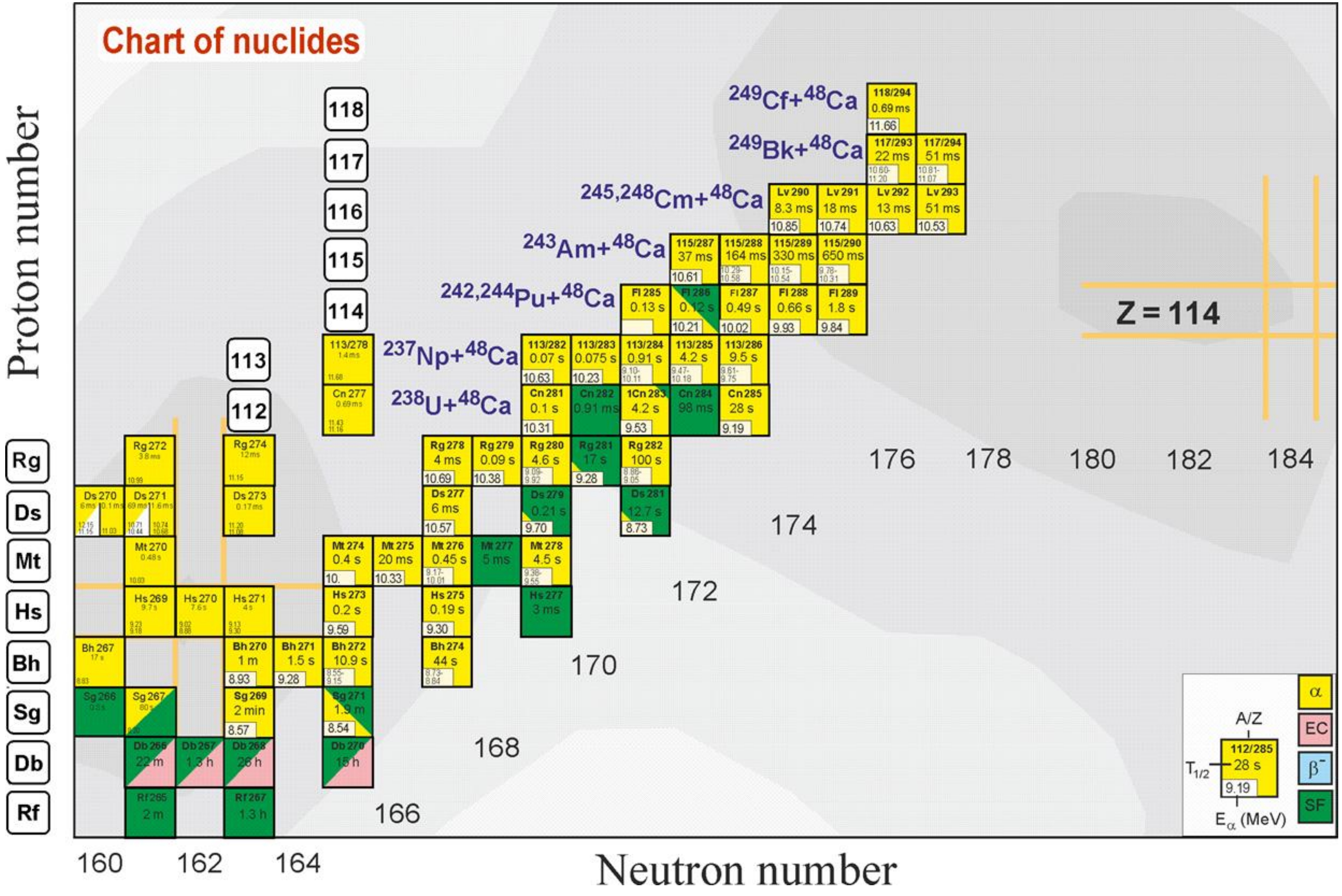
Experimental setups:
- Gas-Filled Recoil Separator (DGFRS-I)
- Separator for Heavy Elements Spectroscopy (SHELS)
- Radio-chemical setups
- Double-arm time-of-flight spectrometer (CORSET)
- Magnetic Analyzer of High Resolution (MAVR)

Dubna gas-filled recoil separator





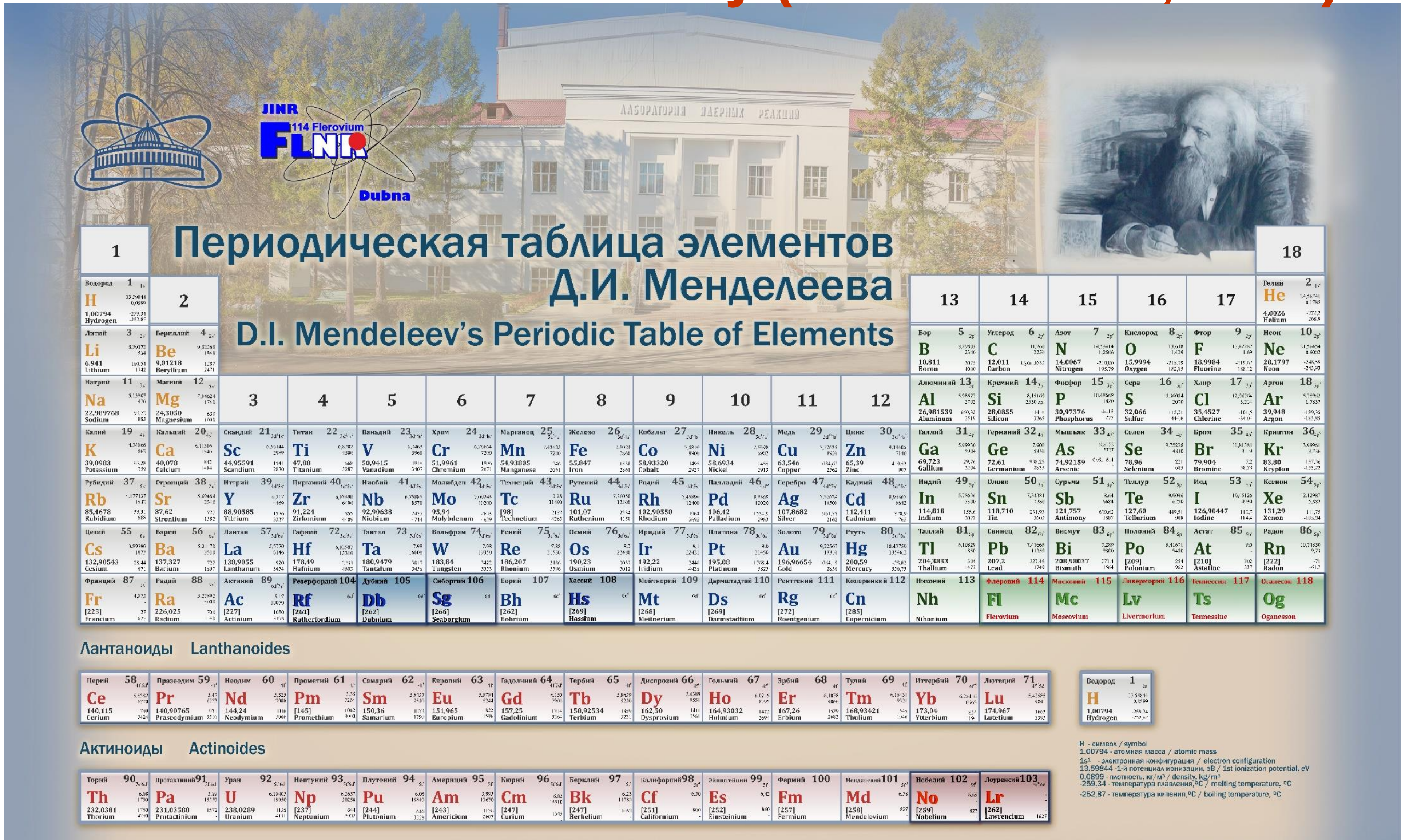
Region of superheavy nuclei.
Recent achievements: 6 new elements and > 50 new isotopes of SHE



Confirmations
(2007-2014)

A, Z	Setup	Laboratory	Published
$^{283}112$	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)

Mendeleev’s Table Today (since Nov. 28, 2016)



10 of 18 elements discovered during last 60 years

were first synthesized in Dubna

I U P A C

International Union of Pure and Applied Chemistry

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:

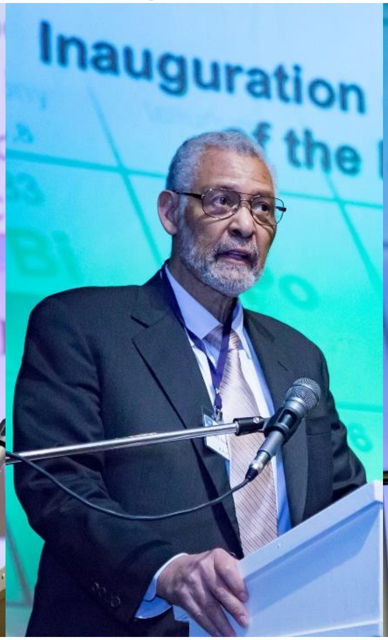
Nihonium (Nh) for element 113,
Moscovium (Mc) for element **115**,
Tennessine (Ts) for element **117,** and
Oganesson (Og) for element **118**.

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

Inauguration of elements 115 (Moscovium), 117 (Tennessine), 118 (Oganesson)

Prof. N. Tarasova
IUPAC

Dr. K. Reed
IUPAP



Prof. O. Vasilieva
Minister of S&E, Russia

Prof. L. Kostov
CPP of JINR Member States

Moscow
Central House of Scientists
of RAS
March 2, 2017

Superheavy Elements (SHE) Factory – the Goals

- **Experiments at the extremely low (σ<100 fb) cross sections:**
  - Synthesis of new SHE in reactions with ^{50}Ti, ^{54}Cr ...(119, 120);
  - Shaping of the region of SHE (synthesis of new isotopes of SHE);
  - Study of decay properties of SHE;
  - Study of excitation functions.

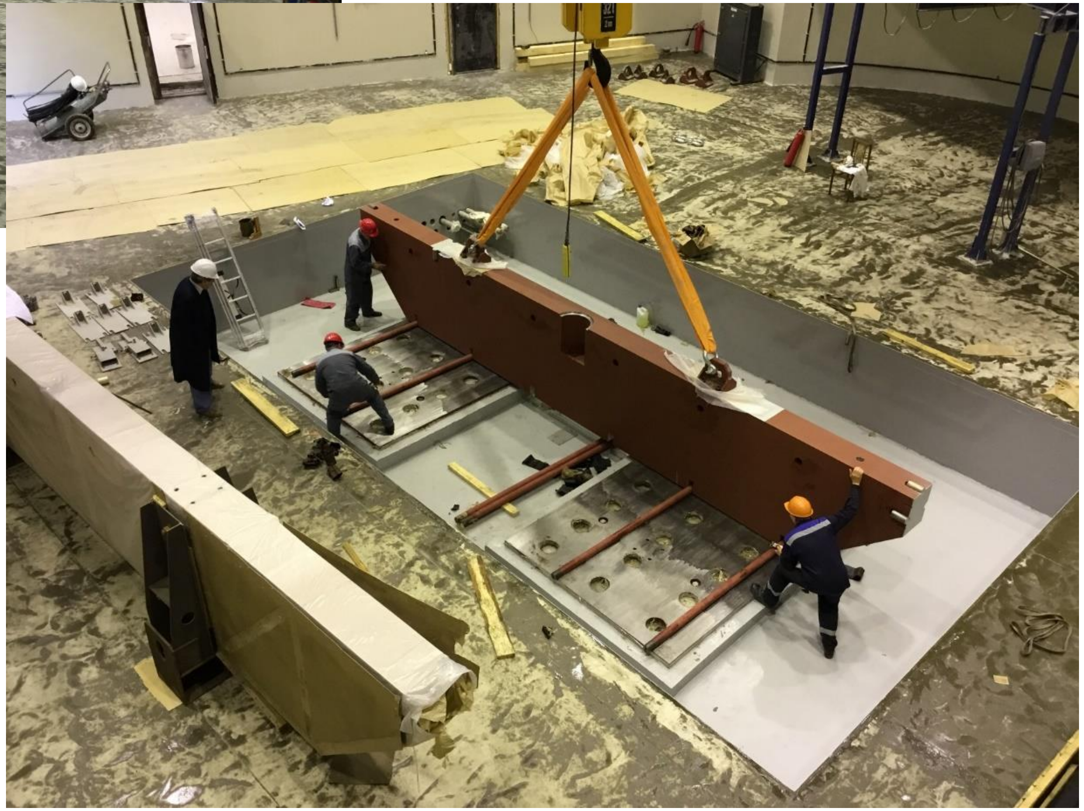
- **Experiments requiring high statistics:**
  - Nuclear spectroscopy of SHE;
  - Precise mass measurements;
  - Study of chemical properties of SHE.

Superheavy Elements Factory

Assembling of the DC-280 main magnet

15/09/2016, 9:00

Same day, 14:35

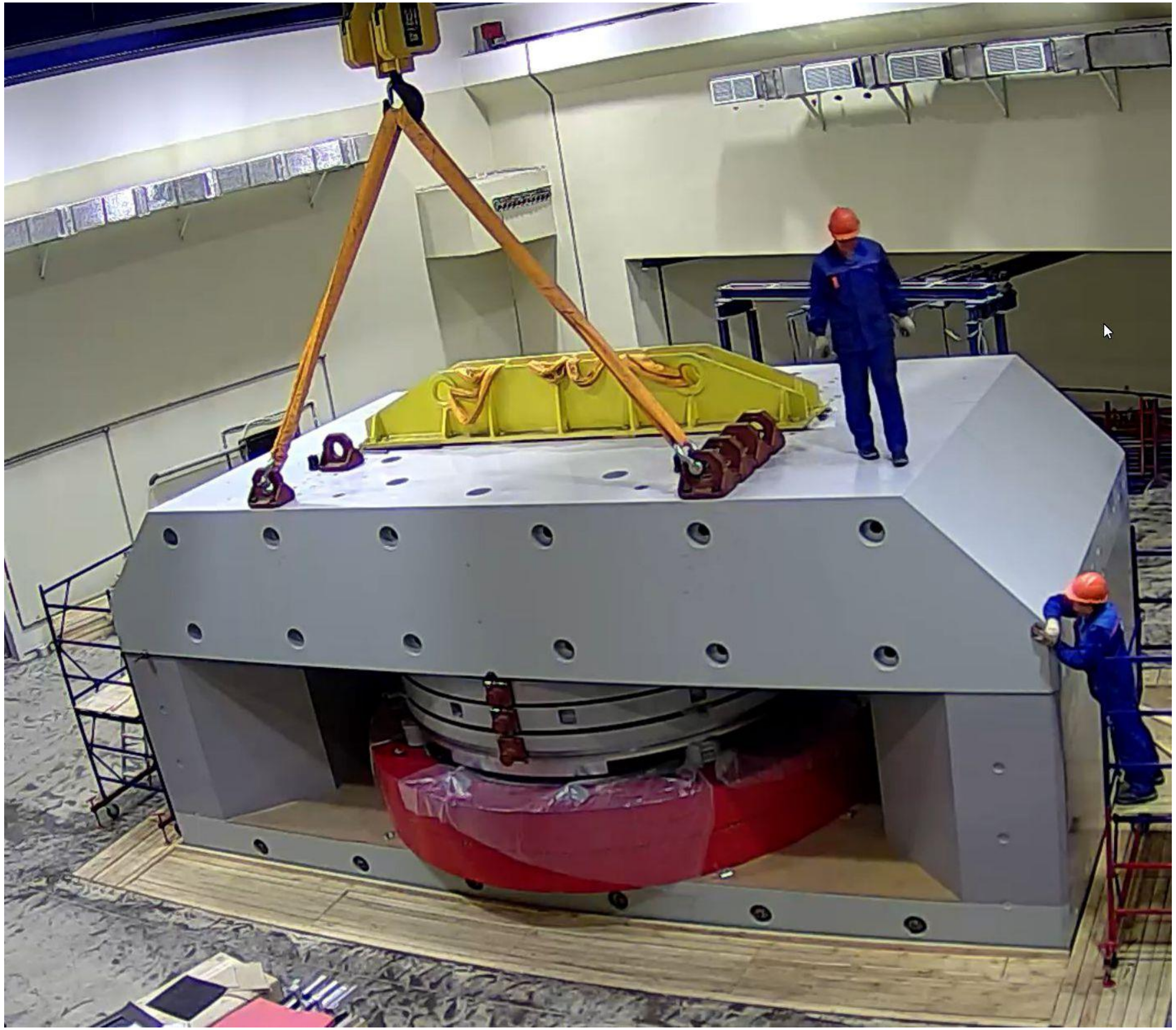


Assembling of DC-280 magnet
28 Sep 2016, 08:53

Assembling of DC-280 magnet
18 Oct 2016, 11:02

Assembling of DC-280 magnet
31 Oct 2016, 15:52

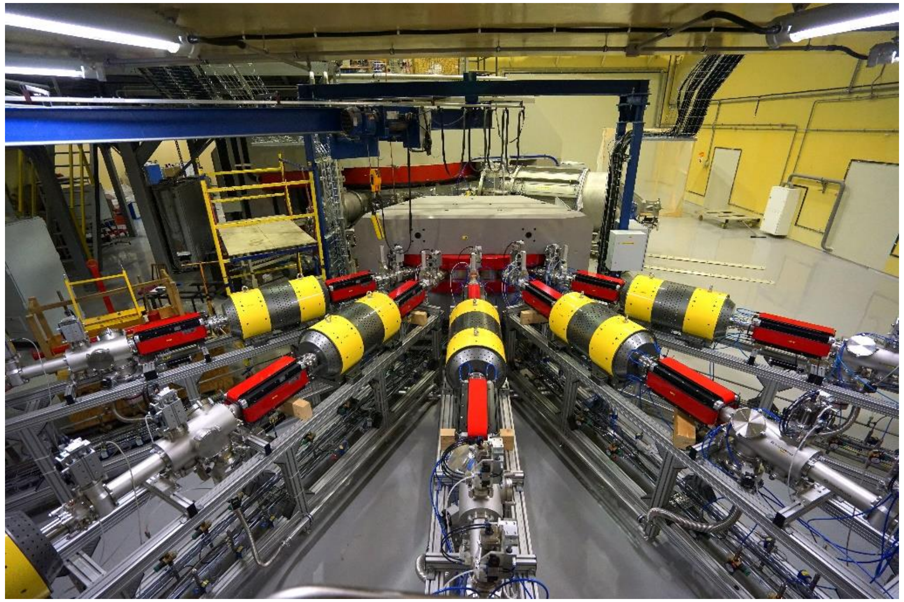
Assembling of DC-280 magnet
03 Nov 2016, 10:00

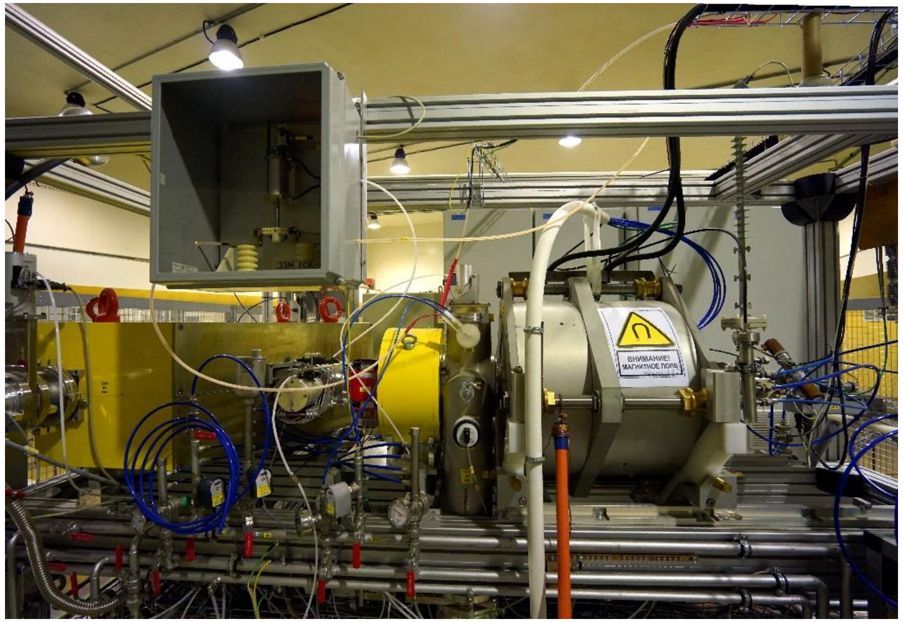


Magnet of DC-280 cyclotron – ready for testing

18.01.2017 http://lideo.ru/embed/4655

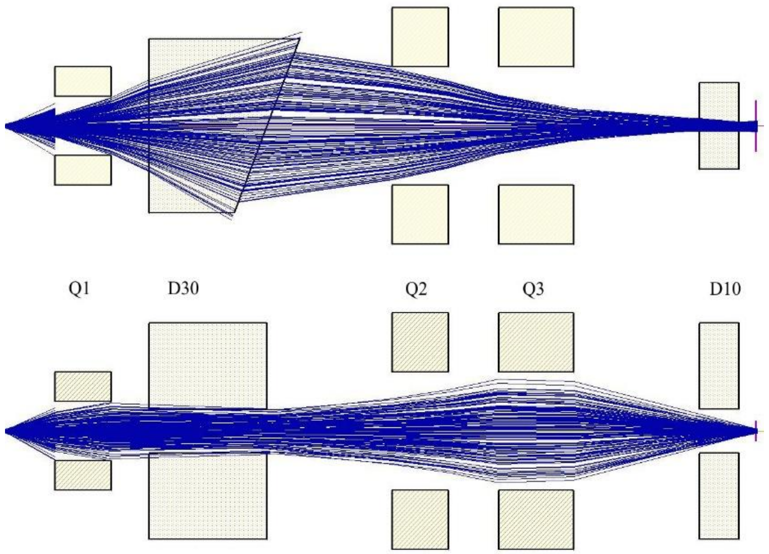
Specialized high-current cyclotron DC-280





DC-280 (expected) E=4÷8 MeV/A		
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	1×10^{14}
^{54}Cr	5	2×10^{13}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

New gas-filled separator



Reaction	Transmission
$^{244}Pu(^{48}Ca,3n)^{289}114$	60 %
$^{244}Pu(^{58}Fe,4n)^{298}120$	75 %

Reactions of Synthesis
Act. + ^{48}Ca

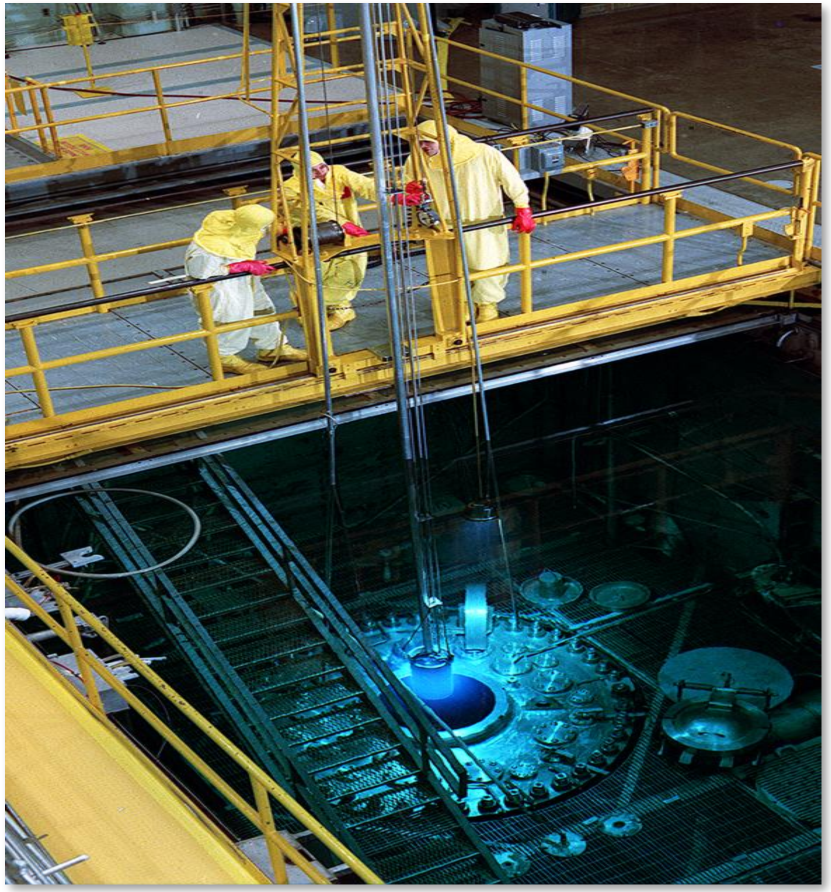
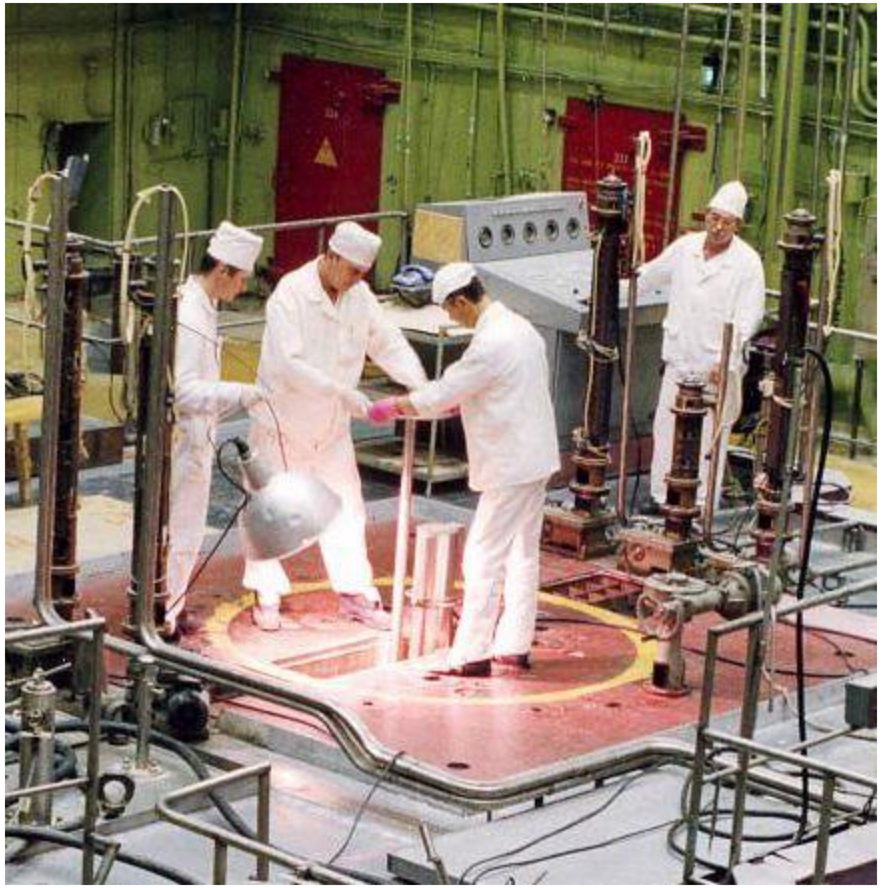
Projectiles ^{48}Ca produced by Heavy Ion Accelerator U-400;

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: $(0.3\text{-}3.0) \cdot 10^{19}$

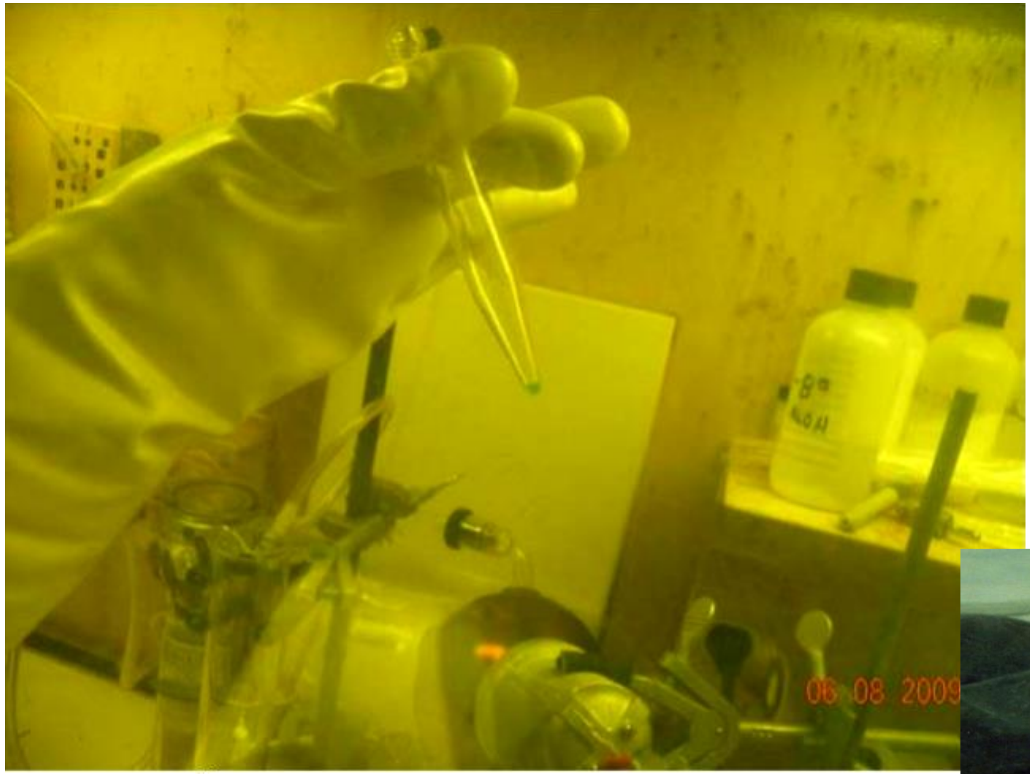
Target materials	Producer	Isotope enrichment (%)
^{237}Np	IAR	99.3
^{239}Pu	RFNC	---
^{240}Pu	IAR/ORNL	99.98
^{242}Pu	RFNC/ORNL	99.98
^{244}Pu	ORNL	98.6
^{243}Am	IAR / ORNL	99.9
^{245}Cm	IAR	98.7
^{248}Cm	IAR /ORNL	97.4
^{249}Bk	ORNL	≥ 95
^{249}Cf	IAR/ORNL	97.3
$^{249,250,251}Cf$	ORNL	(50+14+36)%

0,35-0,40 mg /cm2 - ≈ 12 mg

Isotope reactors

HFIR, ORNL, Oak Ridge, USA, 85 MW	CM-3, IAR, Dimitrovgrad, RF, 100 MW
	

22 mg of ^{249}Bk have been produced in HIFR ORNL

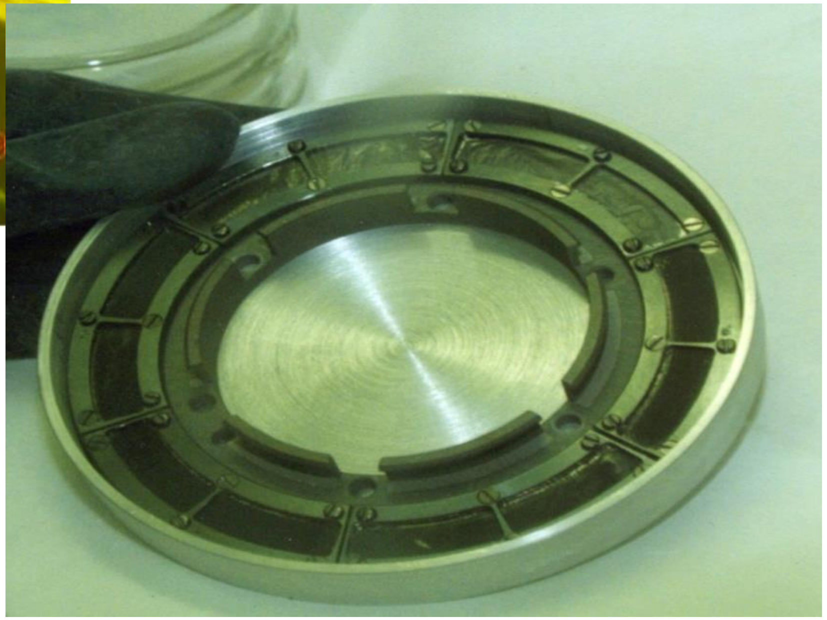


$Bk(NO_3)_3$Product

Prices per 1 mg

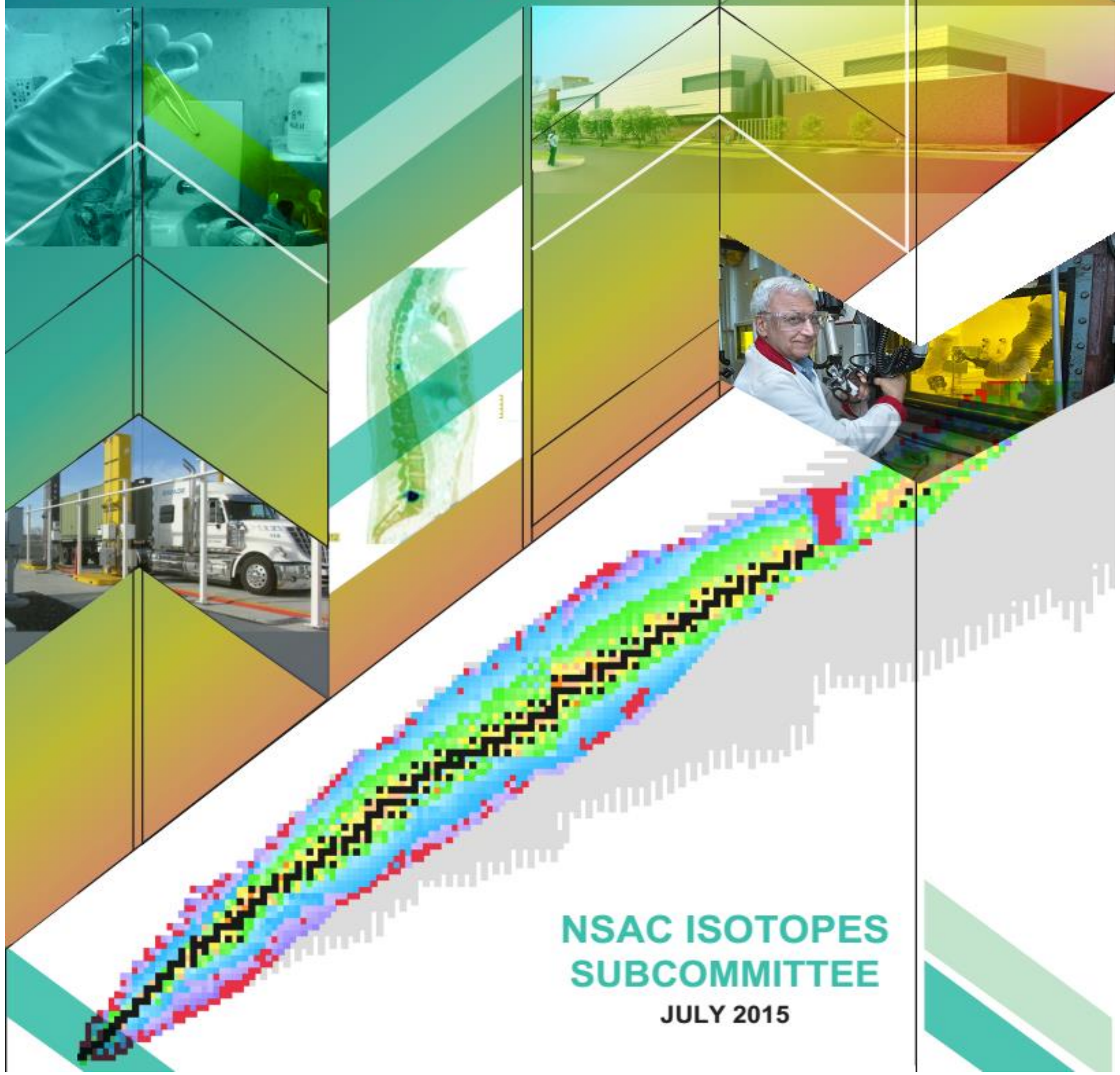
$^{197}Au \approx 0.045$ US$
$^{nat}U_3O_8 \approx 0.03$ US$
$^{239}Pu \approx 4$ US$
$^{249}Cf \approx 60\,000$ US$

Target wheel



MEETING ISOTOPE NEEDS AND CAPTURING OPPORTUNITIES FOR THE FUTURE:

THE 2015 LONG RANGE PLAN FOR THE DOE-NP ISOTOPE PROGRAM



NSAC ISOTOPES SUBCOMMITTEE

JULY 2015

Future Isotopes for Use in Physics and Chemistry

- Isotopes with high isotopic purity required for continued production of superheavy elements and exploration of the island of stability include: $^{233,235}U$, ^{237}Np, $^{239,240,242,244}Pu$, ^{243}Am, $^{245,248}Cm$, ^{249}Bk, and $^{249,251}Cf$. Note that with new accelerator facilities with higher beam intensities coming on-line (such as the Super Heavy Element Factory in Dubna, Russia), demand for these isotopes will increase because thicker and larger targets will be required; current targets require ~20 mg whereas future targets are envisioned to require > 100 mg. Note also that high isotopic purity may necessitate usage of an isotope separator capable of separating radioactive material. Isotopes with high isotopic purity required for chemical study include: ^{248}Cm, ^{249}Bk, $^{249,251}Cf$, $^{252,254}Es$, and ^{257}Fm. The Isotope Program is working with this community to develop a strategic plan for the materials needed for further studies in this area and then to implement it.

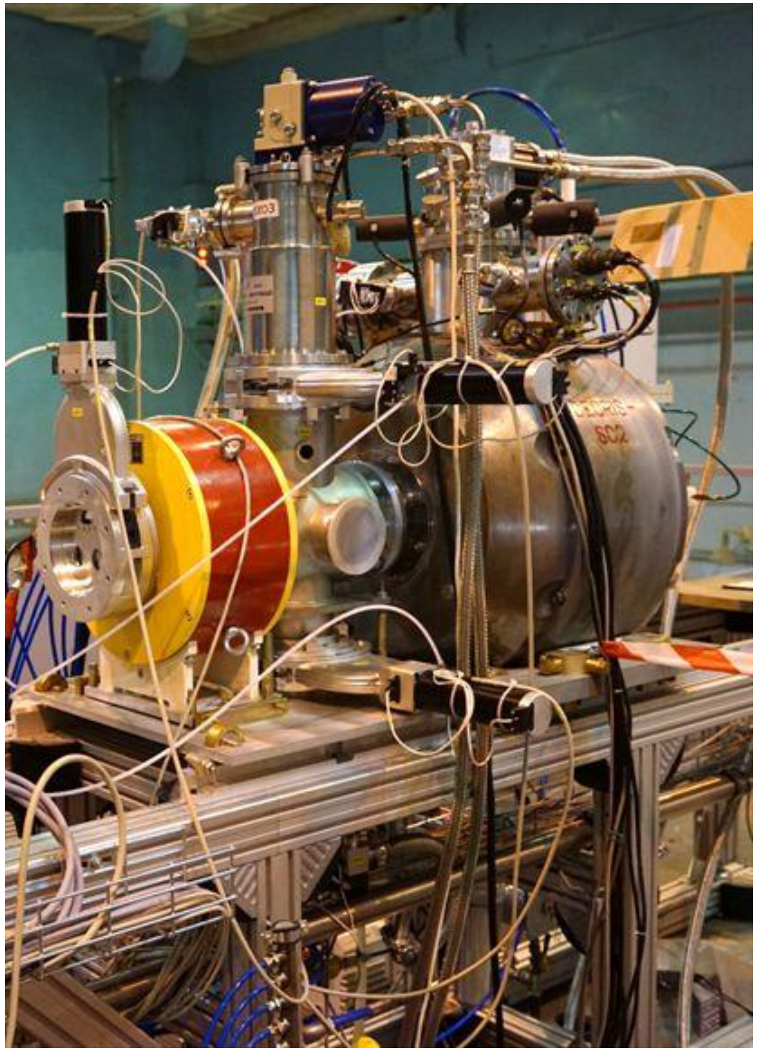
- Mixed and mass separated actinides for chemical and physical studies of transuranium and trans-neptunium isotopes namely ^{237}Np; ^{242}Pu, ^{244}Pu, ^{243}Am, ^{248}Cm, ^{249}Cf, ^{249}Bk, ^{251}Cf, $^{253/254}Es$, and ^{257}Fm. ^{248}Cm is the only readily available isotope of curium that can be used in standard radiochemical facility. The world-wide supply of ^{248}Cm is constrained, and the available ^{249}Bk is currently primarily used as target for synthesis of superheavy elements. ^{249}Bk decays to ^{249}Cf and, similar to Cm, ^{249}Cf is the only Cf isotope readily available that can be used in radiochemical laboratory. Specific metallic and/or chemical forms of these isotopes would be most interesting.

Superconducting 18 GHz ECR ion sources

~2 grams of ^{48}Ca

Ion source DECRIS-SC2

Consumption: 0.5-0.8 mg/h



Prices per 1 mg

$^{197}Au \approx 0.045$ US$

$^{nat}U_3O_8 \approx 0.03$ US$

$^{239}Pu \approx 4$ US$

$^{48}Ca \approx 250$ US$

Development of ^{50}Ti beam using MIVOC method

Synthesis of (trimethyl)pentamethyl-cyclopentadienyl titanium

$$TiCl_4 + (CH_3)_5C_5Si(CH_3)_3 \rightarrow Cp^*TiCl_3 + 3CH_3Li \rightarrow Cp^*Ti(CH_3)_3$$

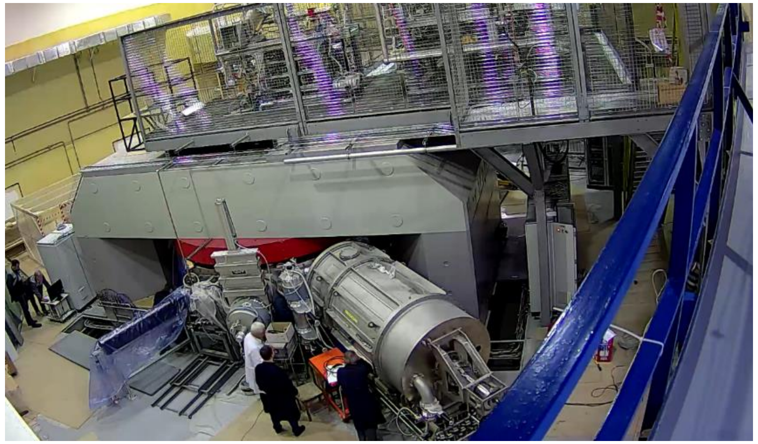
where Cp^* - $(CH_3)_5C_5$

Starting material: $^{50}TiCl_4$ enrichment > 90% - available from Trace Sciences International Inc.

The first step of synthesis was performed at IPHC, the final step at FLNR.
The efficiency of synthesis is more than 90%.

Chemistry laboratory

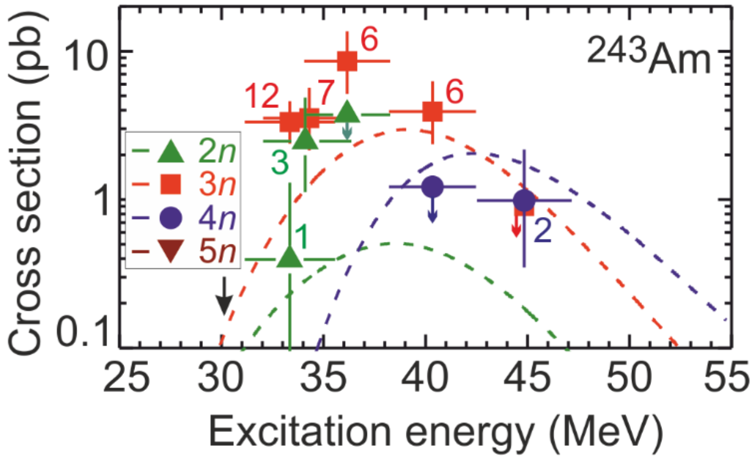
Superheavy Elements Factory



DC-280 cyclotron:
autonomous launching and tuning works

gas-filled recoil separator (GFRS-2):
assembled

existing data for ^{48}**Ca**+^{243}**Am**



the most critical tasks for the end of 2018 – beginning of 2019:

- certifying;
- full commissioning;
- preparing and conducting day-first test experiments (^{48}Ca+^{243}Am);

2nd half of 2019:

- preparing and conducting experiment on synthesis of element 119 in the ^{50}**Ti**+^{249}**Bk** reaction;

Day-one experiments at SHE Factory

Test experiments I:

Test of functionalities of all the systems of the accelerator and gas-filled separator

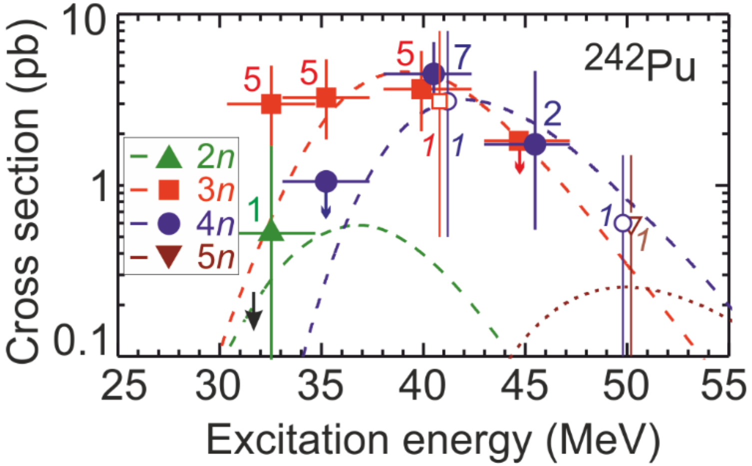
$^{40}Ar+^{nat}Dy$ and $^{18}O+^{208}Pb$

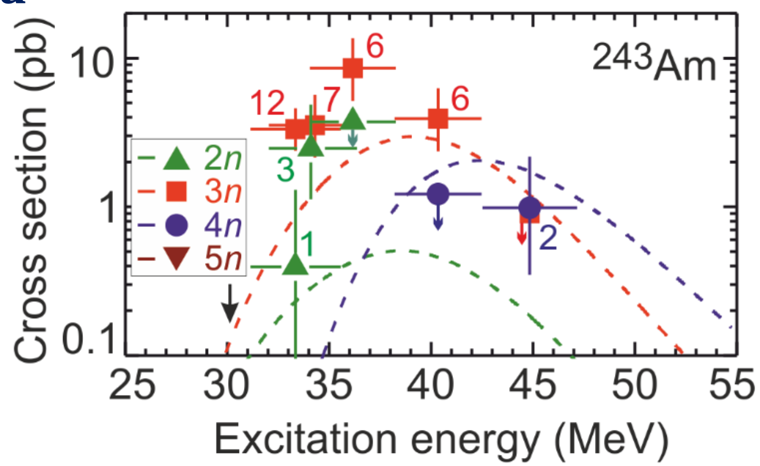
Test experiments II:

$^{48}Ca+^{242}Pu$ and $^{48}Ca+^{243}Am$

1. Enough material to prepare "big" targets
2. Well-studied in previous experiments
3. Relatively large cross sections

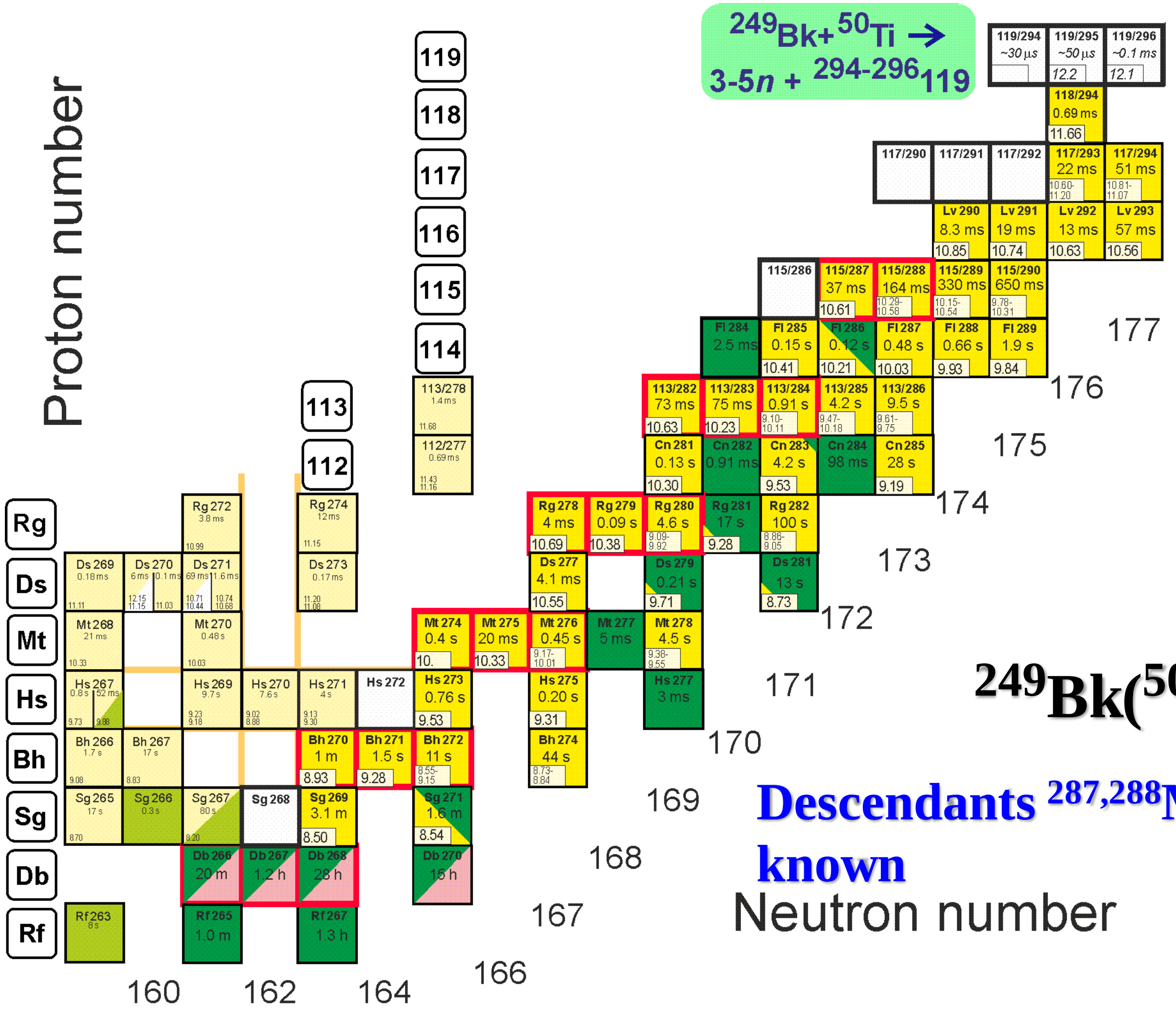
$^{48}Ca+^{242}Pu$ **Existing experimental data** **$^{48}Ca+^{243}Am$**





First experiments at SHE Factory

Synthesis of new element 119



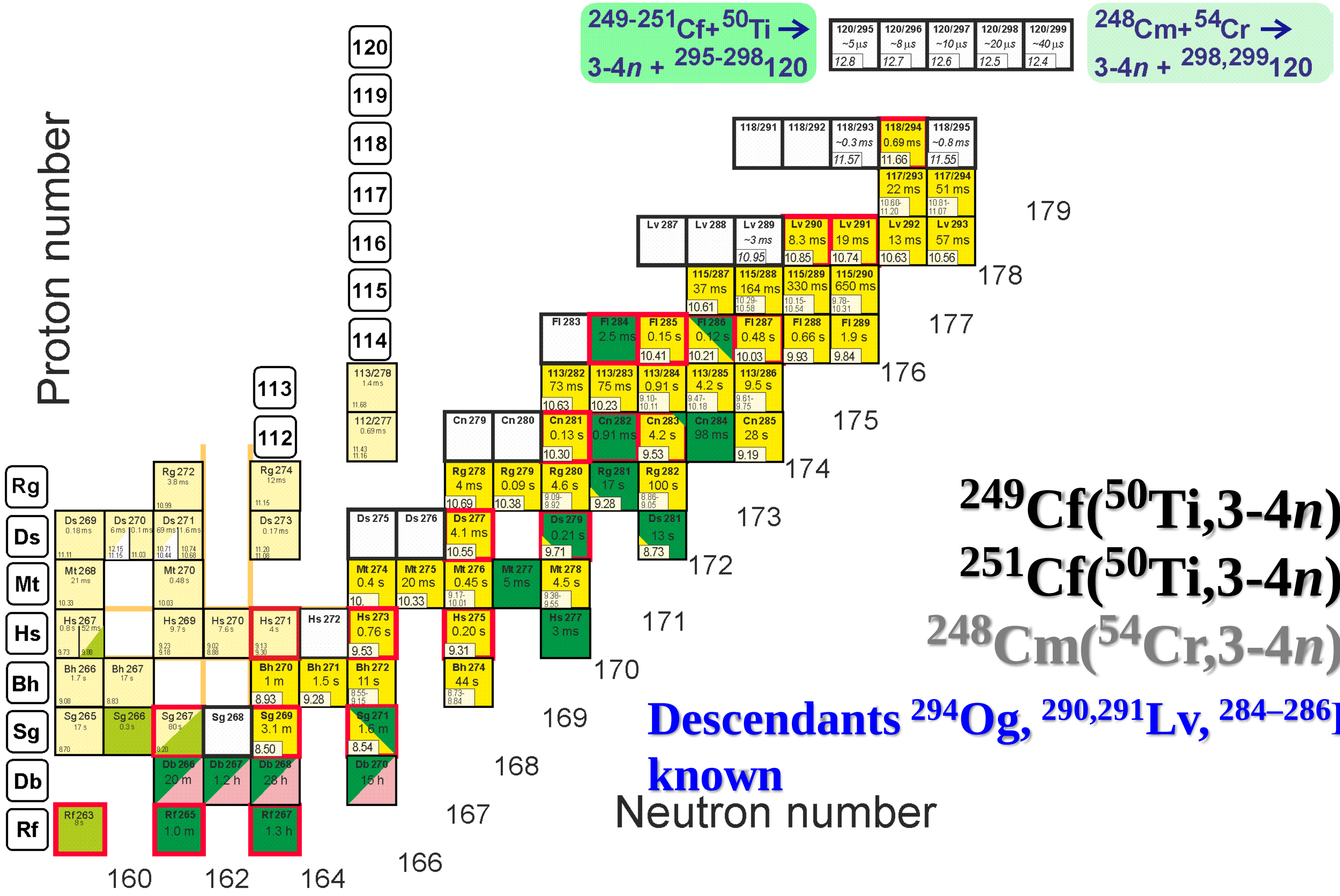
$^{249}Bk(^{50}Ti,3\text{-}4n)^{295,296}119$

Descendants $^{287,288}Mc$, $^{282\text{-}294}Nh$… are known

s=50 fb, h_t=0.3 mg/cm^2, ε_{coll}=0.6, I_{beam}=3 pmA $\rightarrow$ ≈1 event per month

First experiments at SHE Factory

Synthesis of new element 120



^{249}Cf(^{50}Ti,3-4*n*)^{295,296}120

^{251}Cf(^{50}Ti,3-4*n*)^{297,298}120

^{248}Cm(^{54}Cr,3-4*n*)^{298,299}120

Descendants ^{294}Og, ^{290,291}Lv, $^{284–286}$Fl … are known

s=50 fb, h_t=0.3 mg/cm^2, ε_{coll}=0.6, I_{beam}=3 pmA → ≈1 event per month

Thank you for your attention!