Superheavy elements at SHE Factory recent achievements and perspectives

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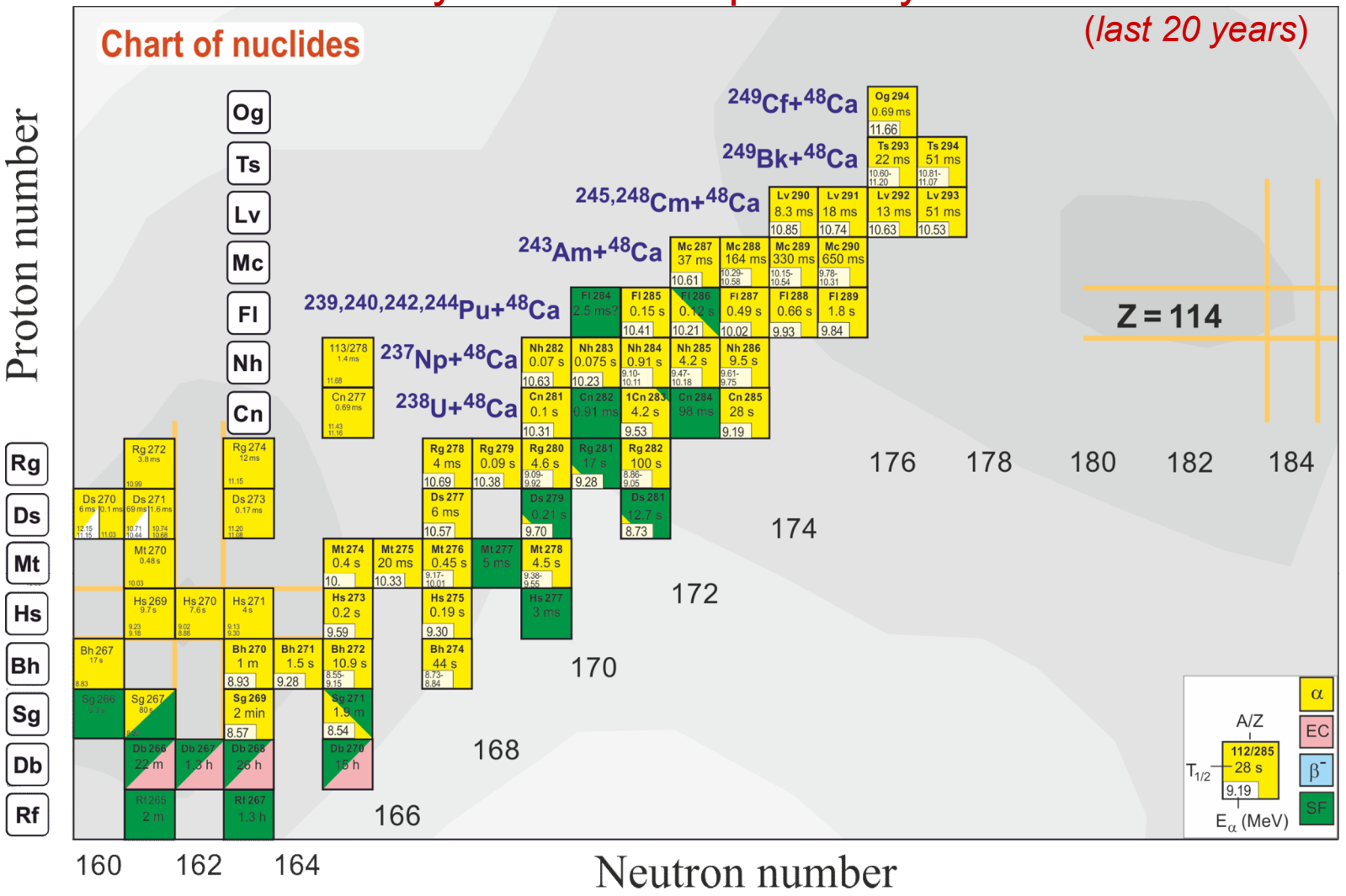
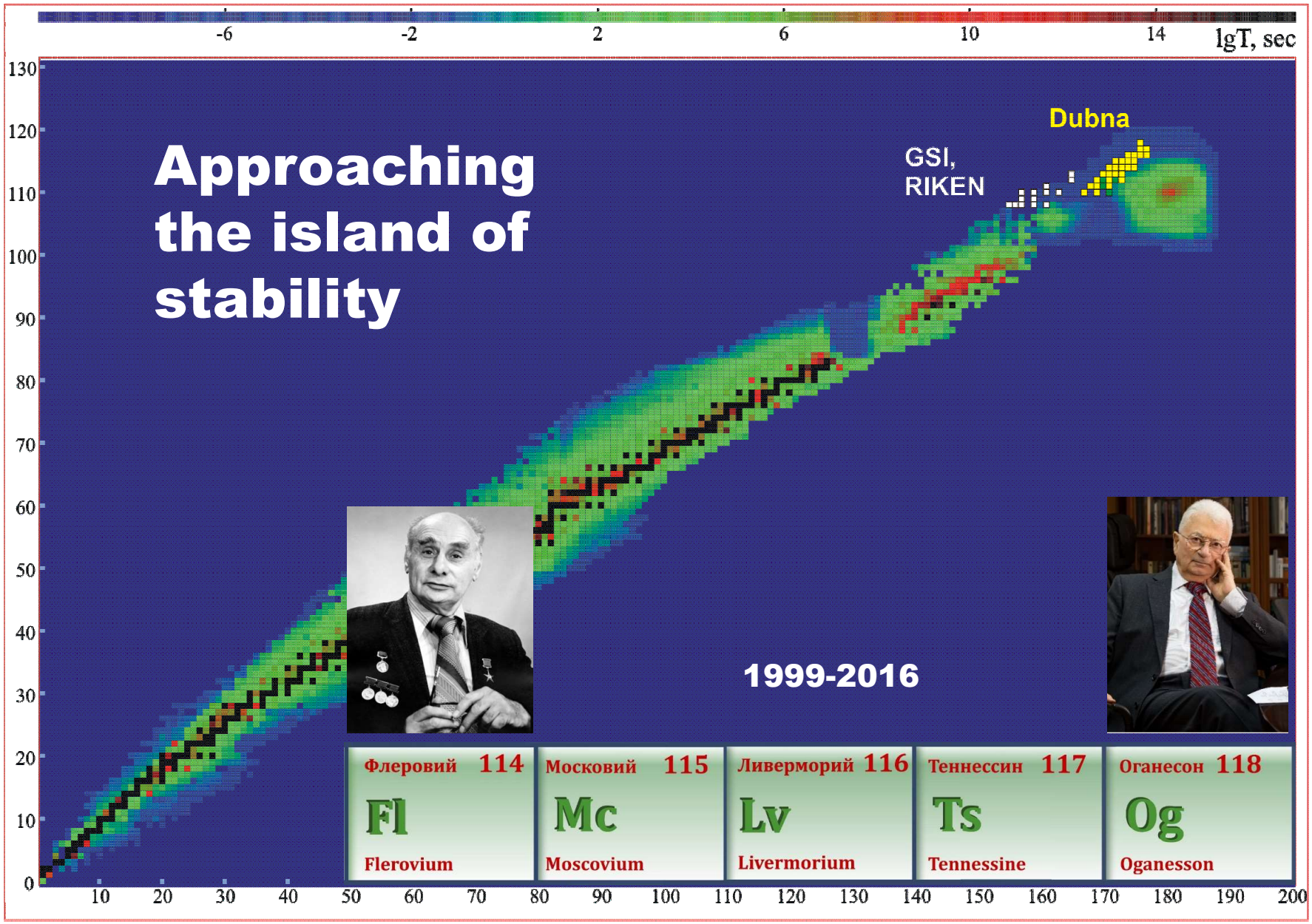
International Workshop on Nuclear and Particles Physics
Almaty, April 24-30, 2022

GREAT PROGRESS

in Synthesis of Superheavy Nuclei




-6
-2
2
6
10
14
lgT, sec
Approaching the island of stability
Dubna
GSI, RIKEN
1999-2016
Флеровий 114
Fl
Flerovium
Московий 115
Mc
Moscovium
Ливерморий 116
Lv
Livermorium
Теннессин 117
Ts
Tennessine
Оганесон 118
Og
Oganesson
0
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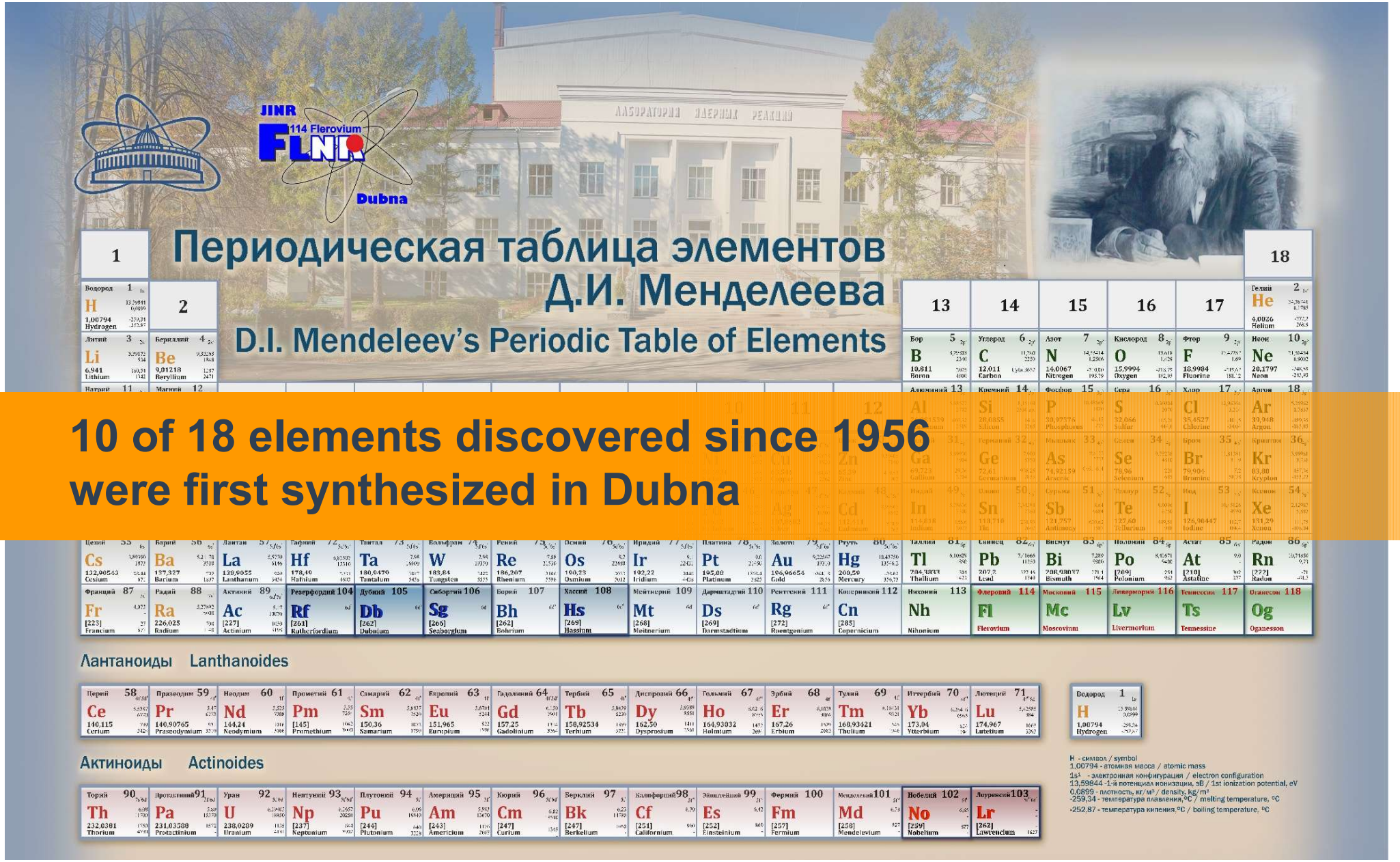

JINR
114 Flerovium
FLNR
Dubna
Периодическая таблица элементов
Д.И. Менделеева
D.I. Mendeleev's Periodic Table of Elements
10 of 18 elements discovered since 1956
were first synthesized in Dubna
Лантаноиды Lanthanoides
Актиноиды Actinoides

DRIBS-III ACCELERATOR COMPLEX

FLEROV LABORATORY OF NUCLEAR REACTIONS

FLNR's basic directions of research:

- Heavy and superheavy nuclei
- Radioactive ion-beam research
- Radiation effects and physical groundwork of nanotechnology
- Accelerator technologies

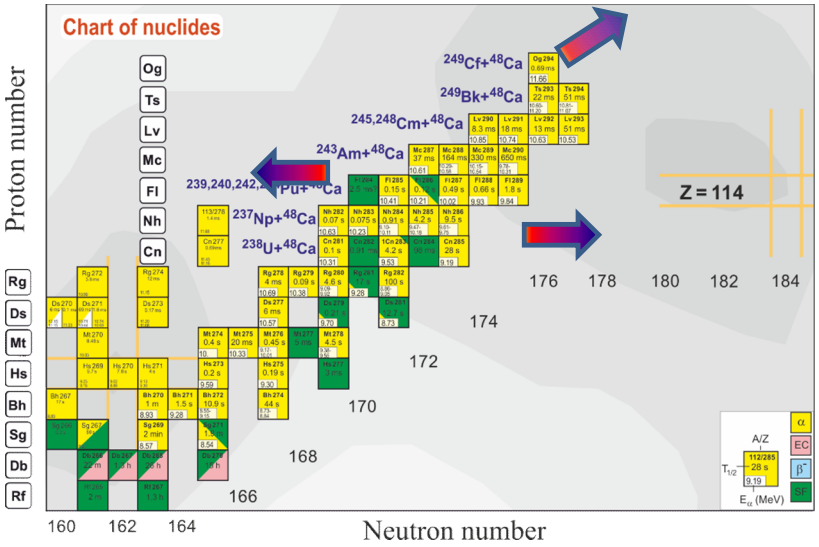
SHE research: Main tasks

Experiments at the extremely low (σ<100 fb) cross sections:

- Synthesis of new SHE with Z = 119 and 120 in reactions with ^{50}Ti, ^{54}Cr ...;
- Synthesis of new isotopes of SHE;
- Study of decay properties of SHE;
- Exploring limits the Island of Stability;
- Study of excitation functions.

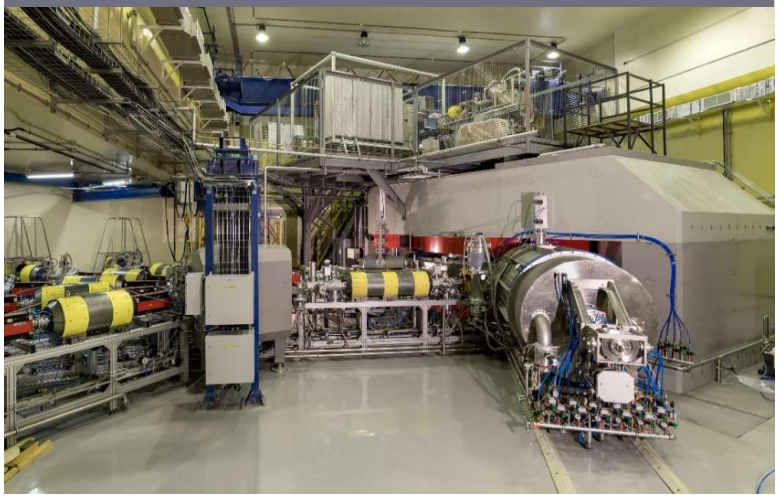
Experiments requiring high statistics:

- Nuclear spectroscopy of SHE;
- Precise mass measurements;
- Study of chemical properties of SHE.



Beam of ^{48}Ca @ DC-280:

- *Intensity: up to 6·10^{13} ions/s, 10 pμA*
- *Energy: 5 - 8 A·MeV*
- *Efficiency: ~50%*



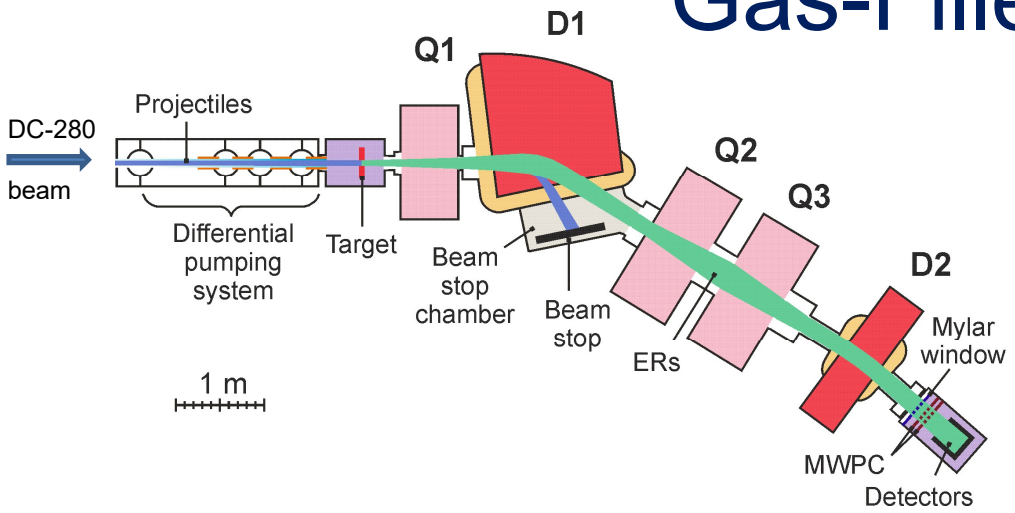
Cyclotron DC-280
Factory of superheavy elements

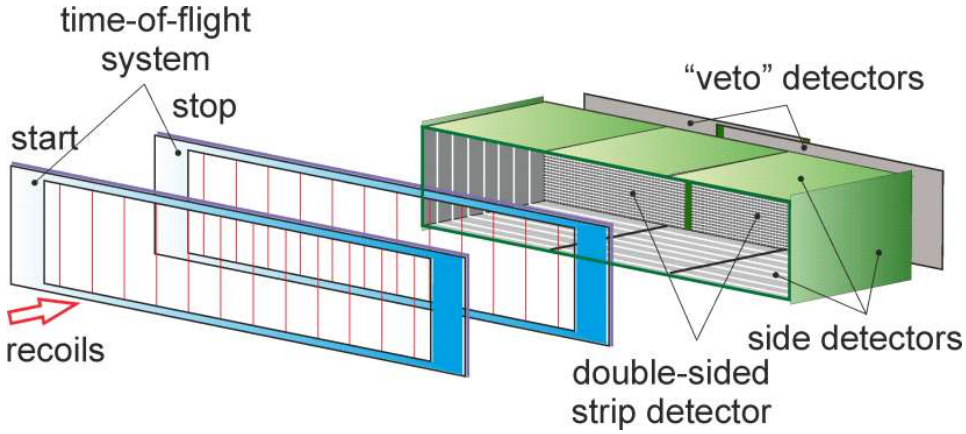
Beam of ^{48}Ca

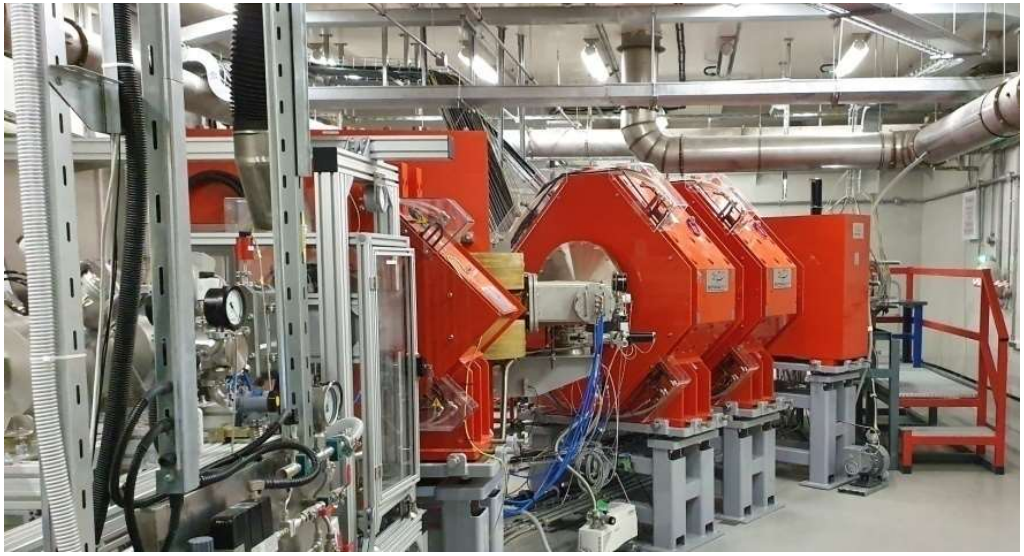
Achieved Intensity:
$4.3 \cdot 10^{13}$ ions/s

Efficiency:
~50%

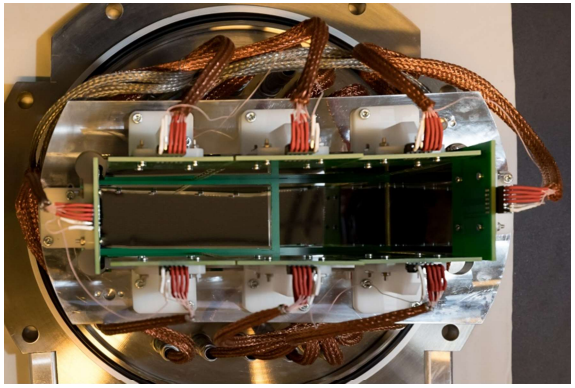
Gas-Filled Separator, **DGFRS-2**







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



60×240 DSSD &
60×120 SSSD
Digital and analog electronics

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

~60 days

Nov.-Dec. 2020
Jan.-Feb. 2021
Jan.-Feb. 2022

Results of the first experiment ^{243}Am + ^{48}Ca

Technical tasks:

- Transmission
- Background
- Image size on detector
- Systematics of charge states
- Test of digital and analog data acquisition systems

Scientific tasks:

- Excitation function for x*n*-evaporation channels
- Decay properties
- Cross sections for the p*xn* channel
- EC branch for ^{288}Mc and ^{284}Nh

I = 1.2-1.3 pμA ~ (7-8)·10^{12} ions/s

Transmission

- From ^{206}**Pb**(^{48}**Ca**,2n)^{252}**No** test reaction: 55±7%
- From ^{243}**Am**(^{48}**Ca**,2-3n)^{288,289}**Mc** reaction:

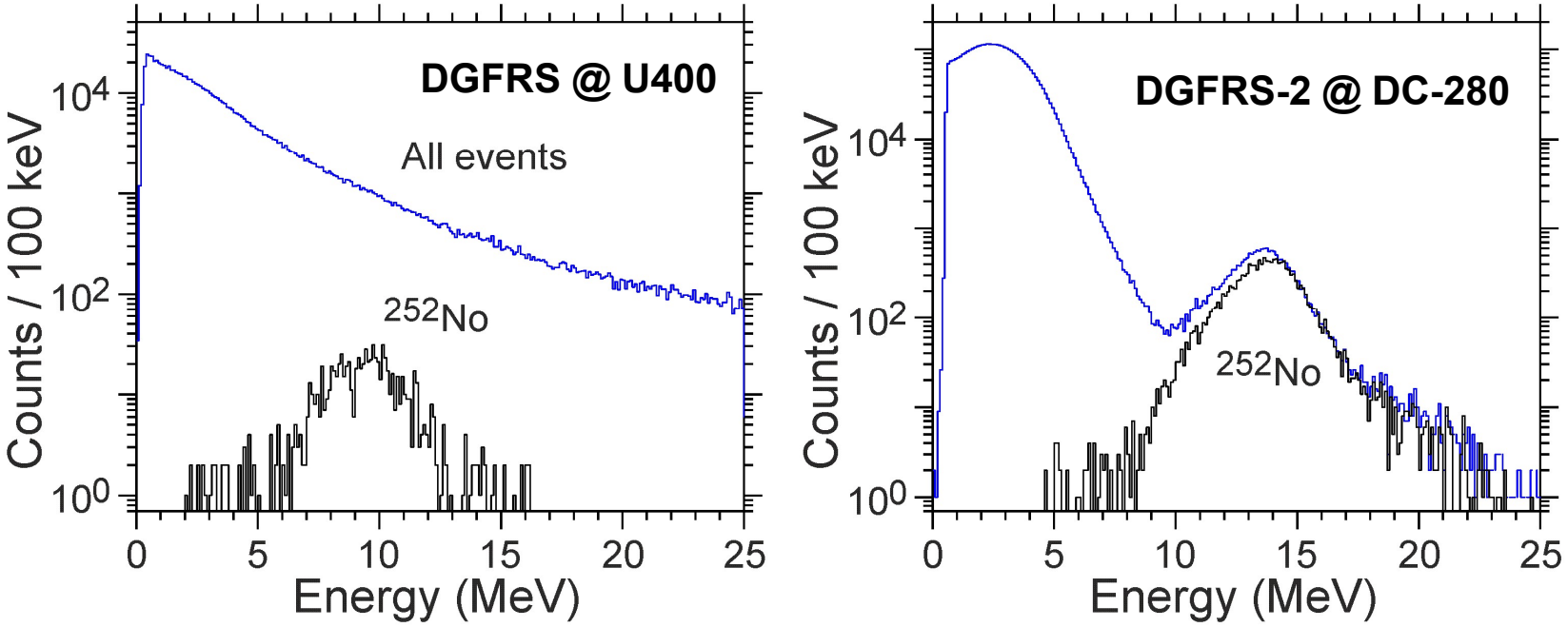
Comparison of results at the same ^{48}**Ca** energy

	DGFRS @ U400	**DGFRS-2 @ DC-280**
Target thickness, mg/cm^2	0.37	0.43
Beam dose, 10^{18}	3.3	3.4
No decay chains	^{288}Mc – 6 ^{289}Mc – 0	^{288}Mc – 13 ^{289}Mc – 2
Yield	1	1.8-2.1

Background conditions

^{206}Pb+^{48}Ca $\rightarrow$^{252}No+2n (Cross section 0.5 mb)

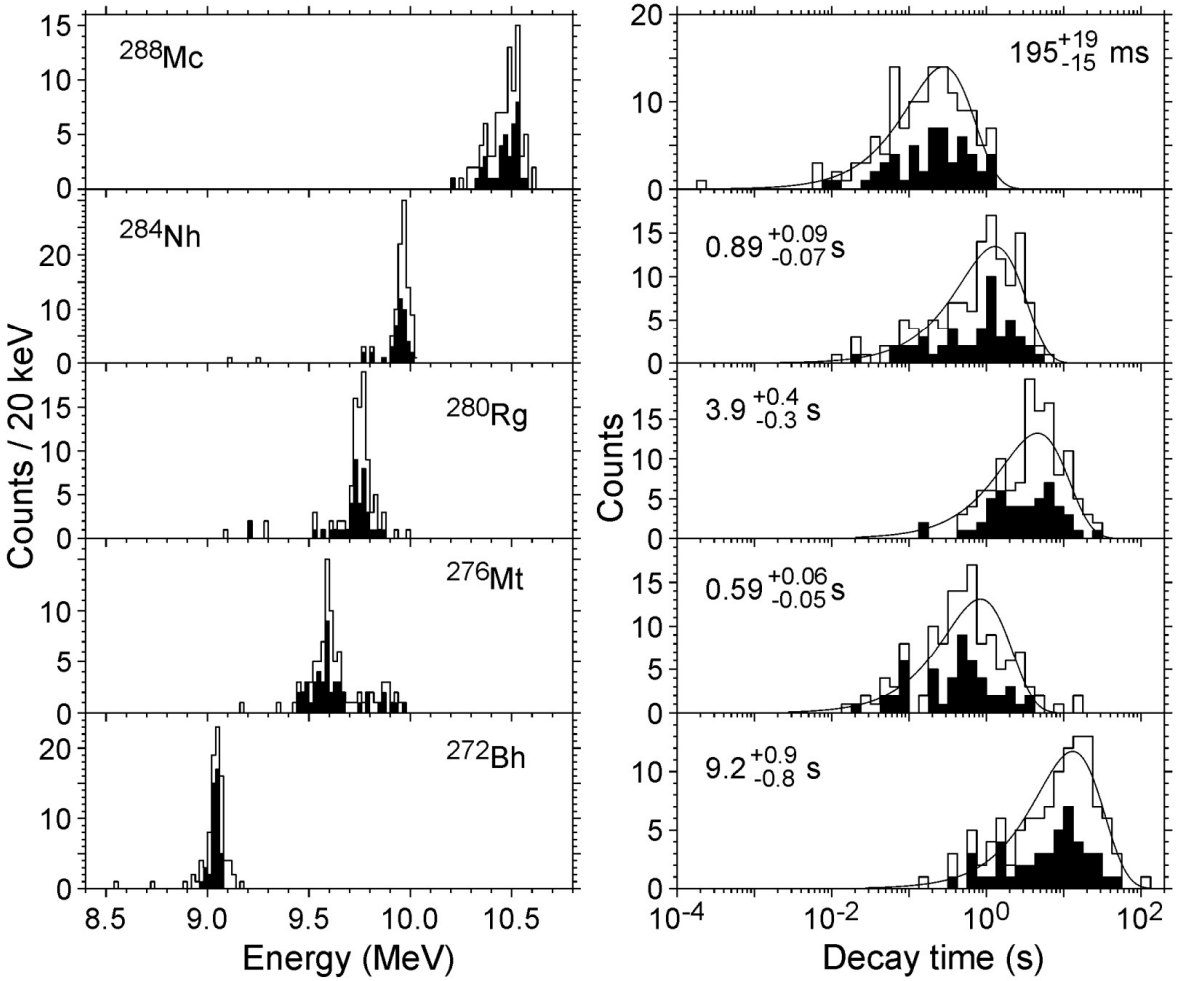
Background suppression is 200+ higher at the DGFRS-2 than at DGFRS



Energy spectra of all the particles registered by MWPC (top blue line) and of ^{252}No (bottom black line) nuclei produced in the ^{206}Pb(^{48}Ca,2*n*) reaction using separators DGFRS (a) and DGFRS-2 (b).

Results of the first experiment

^{288}Mc decay properties

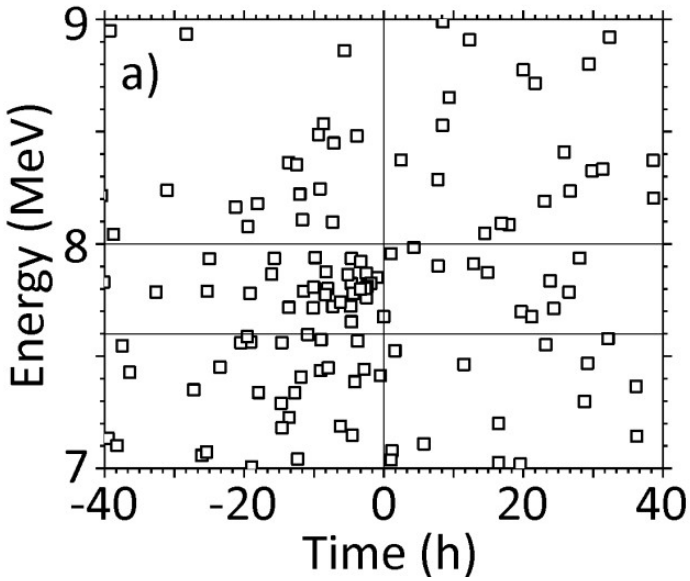


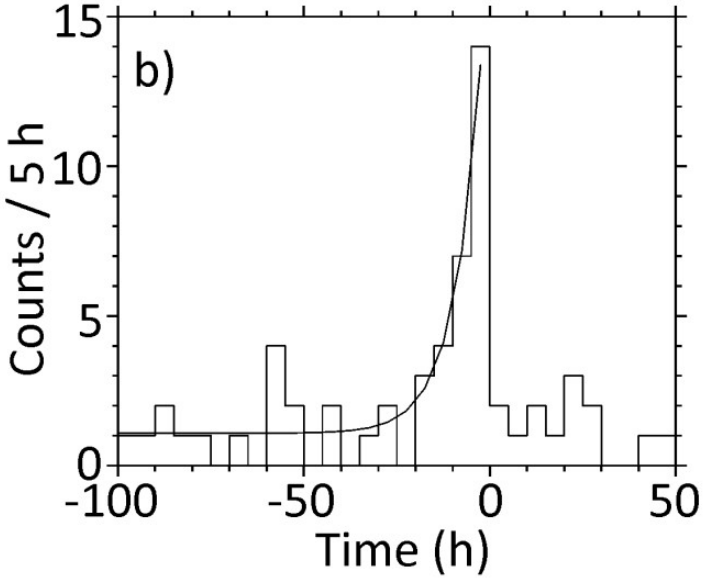
DGFRS, JINR
TASCA, GSI
BGS, LBNL

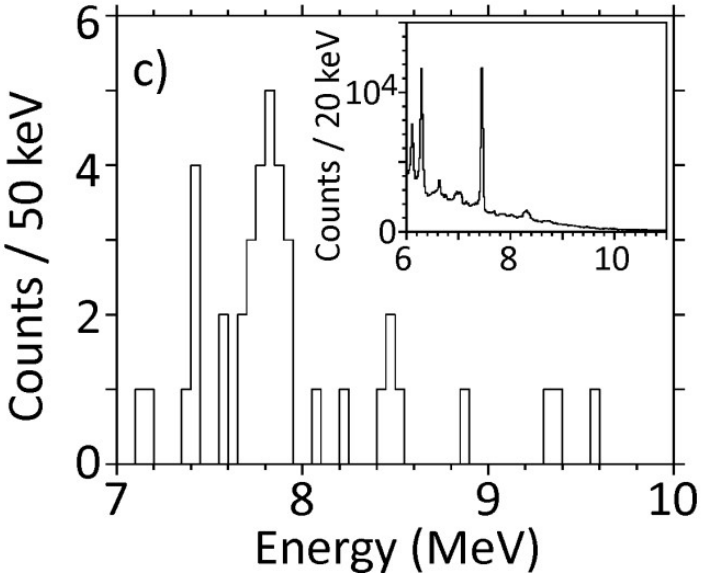
DGFRS-2, JINR

First observation of α–decay of ^{268}Db and new isotope ^{264}Lr

b_α (^{268}Db) = 55 ($^{+20}_{-15}$) % $T_{1/2}$ (^{268}Db) = 16 ($^{+6}_{-4}$) h $T_{1/2}$ (^{264}Lr, SF) = 4.9 ($^{+2.1}_{-1.3}$) h







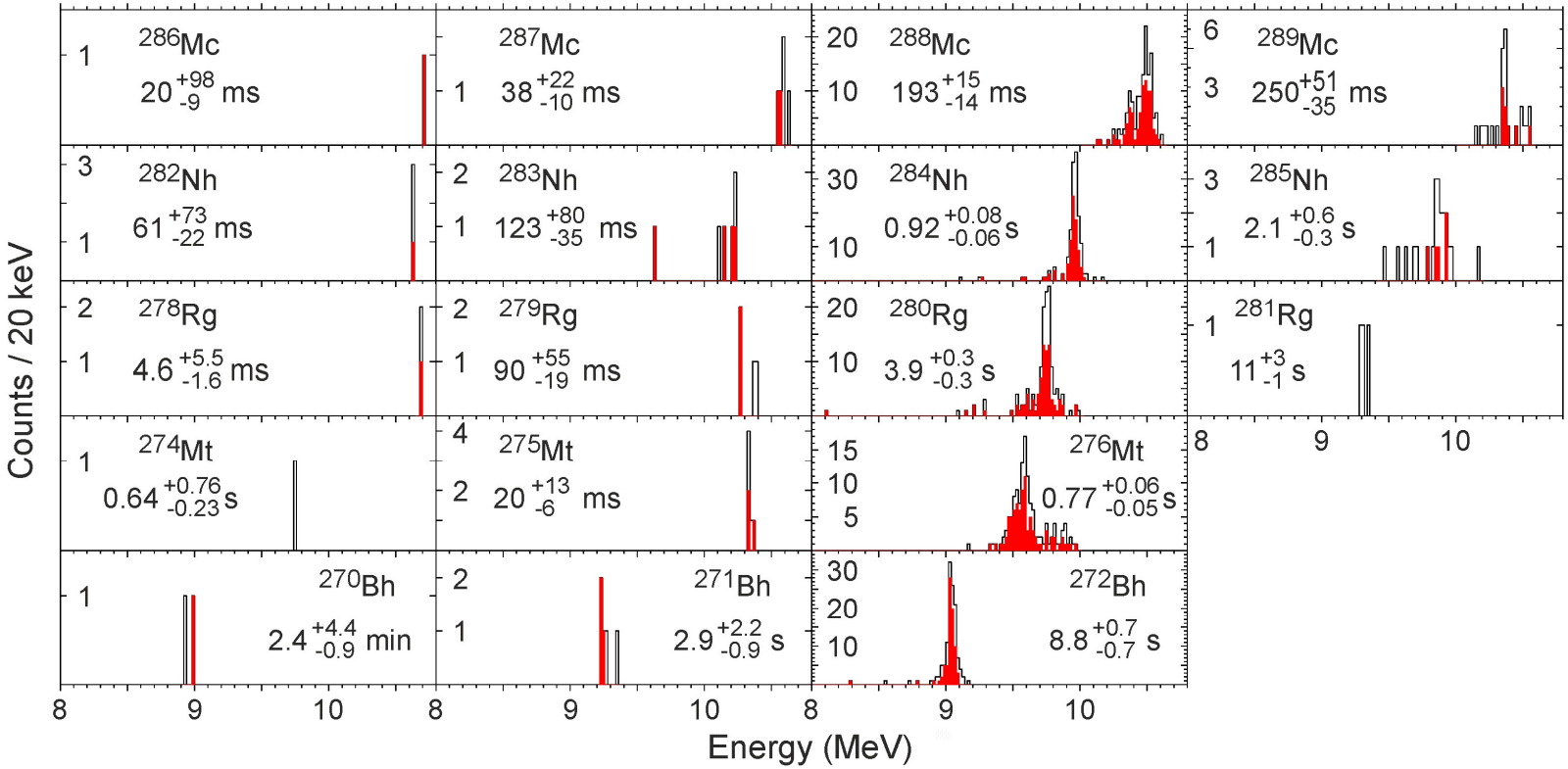
First experiments: statistics summary

E (MeV)	239.1	240.9	242.0	243.9	251.0	259.0	**total**	*before*
Dose, 10^{18}	2.4	2.3	9.2	8.1	2.0	5.0	**29**	
^{286}Mc (*5n*)	-	-	-	-	0	1	**1**	*0*
^{287}Mc (*4n*)	-	-	2	-	1	1	**4**	*3*
^{288}Mc (*3n*)	9	16	52	30	0	3	**110**	*31*
^{289}Mc (*2n*)	-	1	4	5	-	-	**10**	*18*

^{243}Am(^{48}Ca,2-5n)$^{286-289}$Mc Reaction

125 decay chains

Decay properties of 22 isotopes



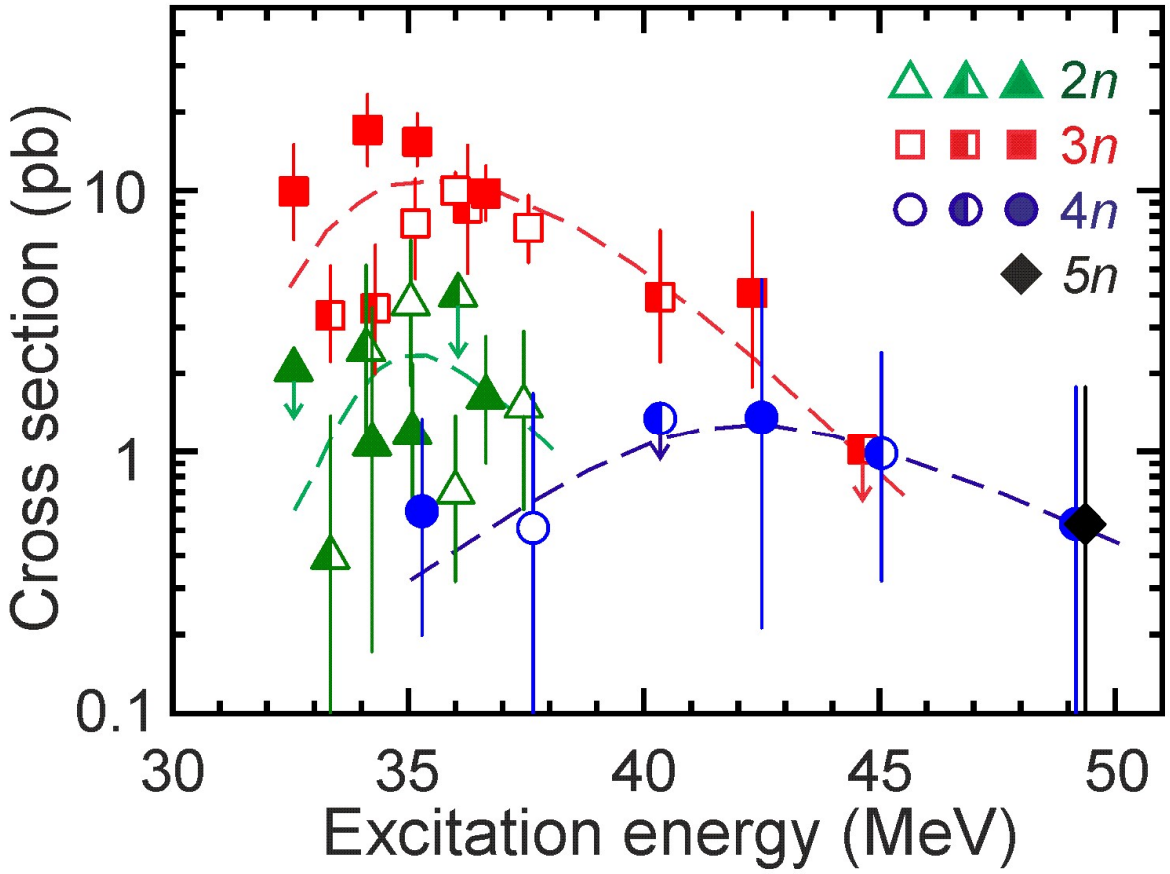
DGFRS, JINR
TASCA, GSI
BGS, LBNL

DGFRS-2, JINR

Results of the first experiments

Excitation function

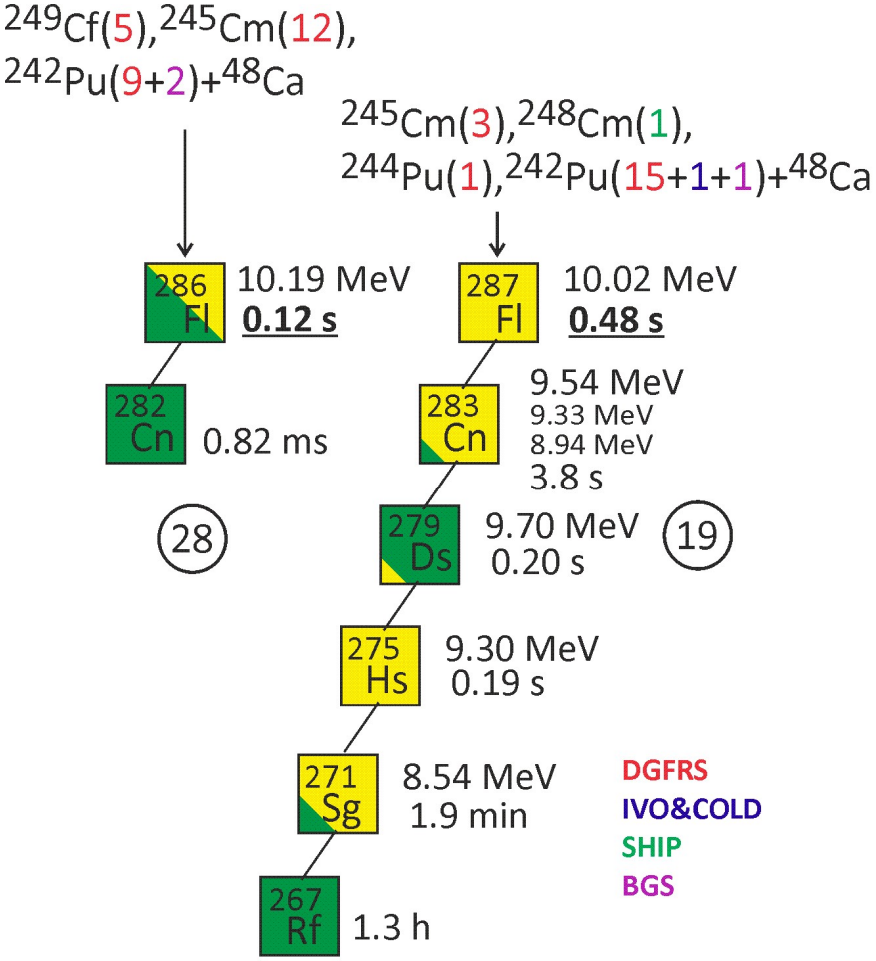
DGFRS (open),
TASCA (half open),
DGFRS-2 (filled)



Completed in June 2021

Preparation of experiment on chemistry of Fl and Cn

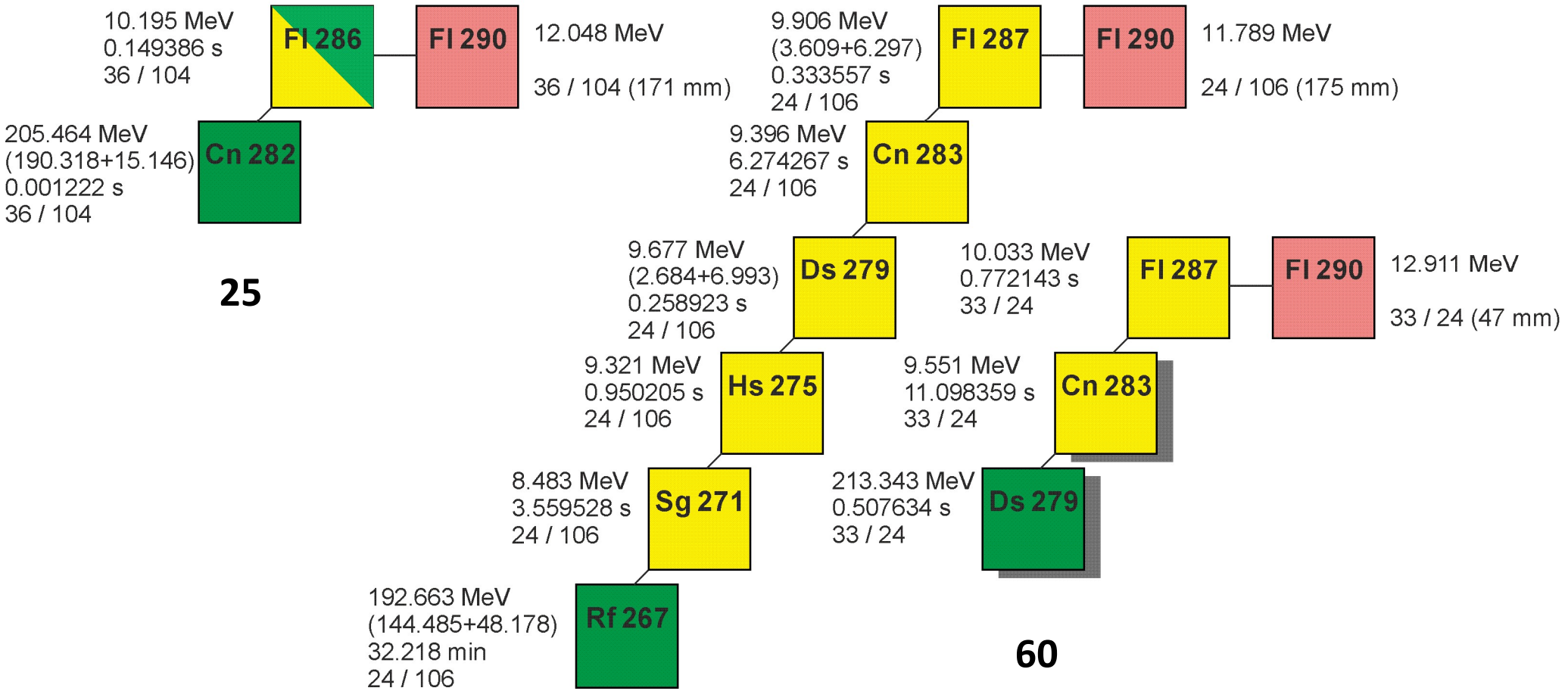
Results of the experiment $^{242}Pu+^{48}Ca$



E=242.5 MeV, Beam dose=11.2 10^{18}
N (^{287}Fl / ^{286}Fl) = 65 / 11
E=247.5 MeV, Beam dose=5.0 10^{18}
N (^{287}Fl / ^{286}Fl) = 4 / 14

I = 0.05, 0.1 … 1, 1.5, 2.0, 2.5, 3 pμA

Results of the first experiment $^{242}Pu+^{48}Ca$

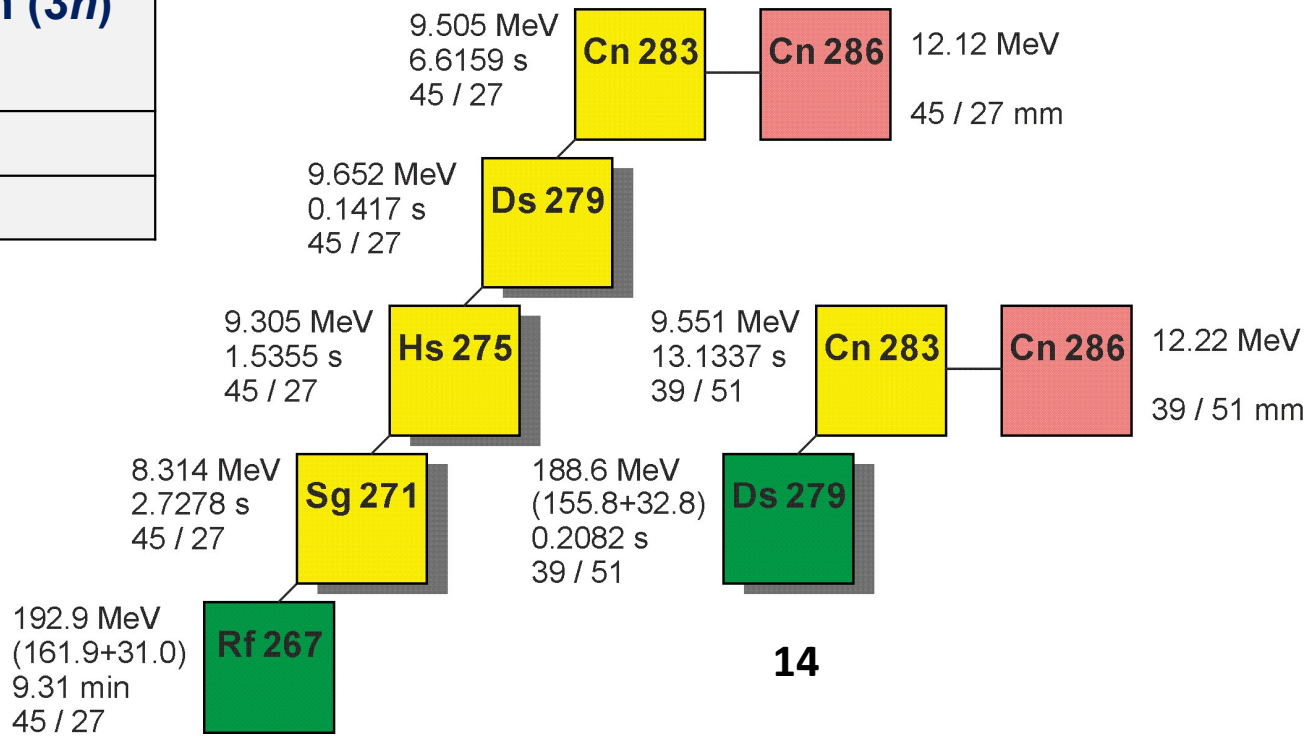


$^{238}U(^{48}Ca,3n)^{283}Cn$ (September – October 2021)

E_{lab} (MeV)	beam dose ×10^{18}	^{283}Cn (3*n*)
234.4	12.1	4
231.1	13.5	12

beam: 0.5, 1, … 6.5 pμA

target: 24 cm

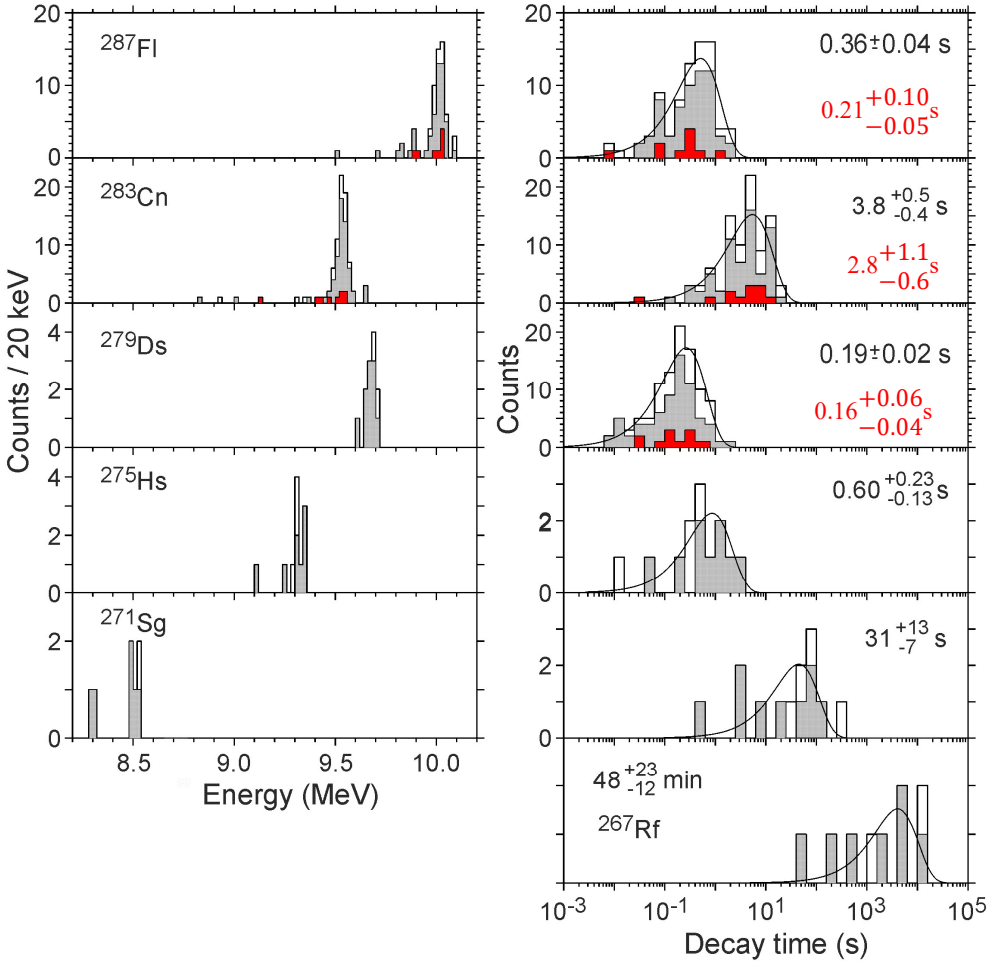


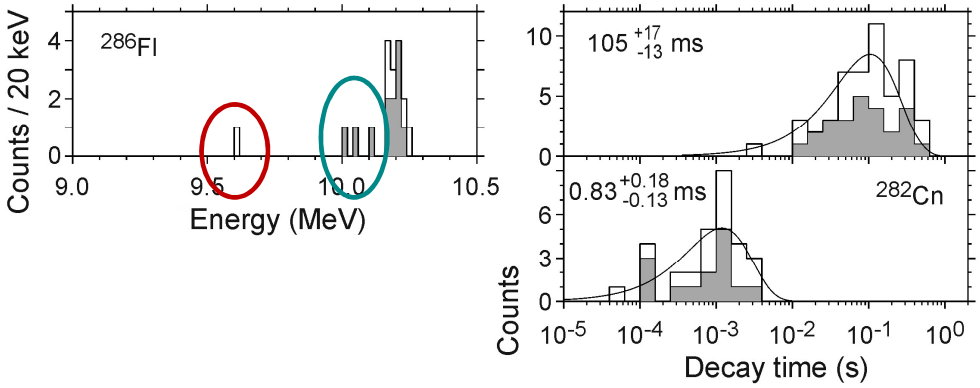
14

3 (DGFRS-1) +
1 (SHIP) +
9 (^{242}Pu) +
2

^{242}Pu(^{48}Ca,3-4n)^{286,287}Fl and ^{238}U(^{48}Ca,3n)^{283}Cn

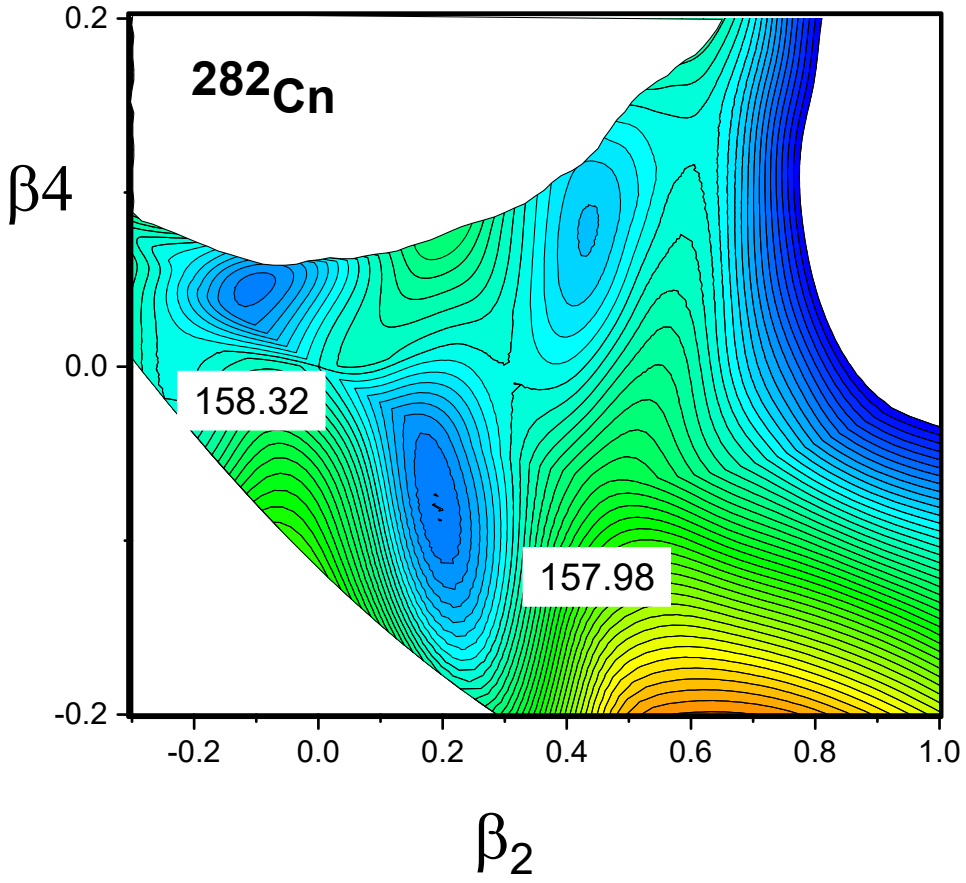
Decay properties of 8 isotopes





- ***^{287}Fl, ^{283}Cn, and ^{279}Ds**: decay through different states*
- ***^{286}Fl**: α–decay line 9.6 MeV for was not observed*
  A. Såmark-Roth et al., PRL (2021)
- ***^{286}Fl**: decay on 2^+ rotational state **^{282}Cn** or through isomeric states*

Presumable α-decay of ^{286}Fl on rotational 2^+-state of ^{282}Cn

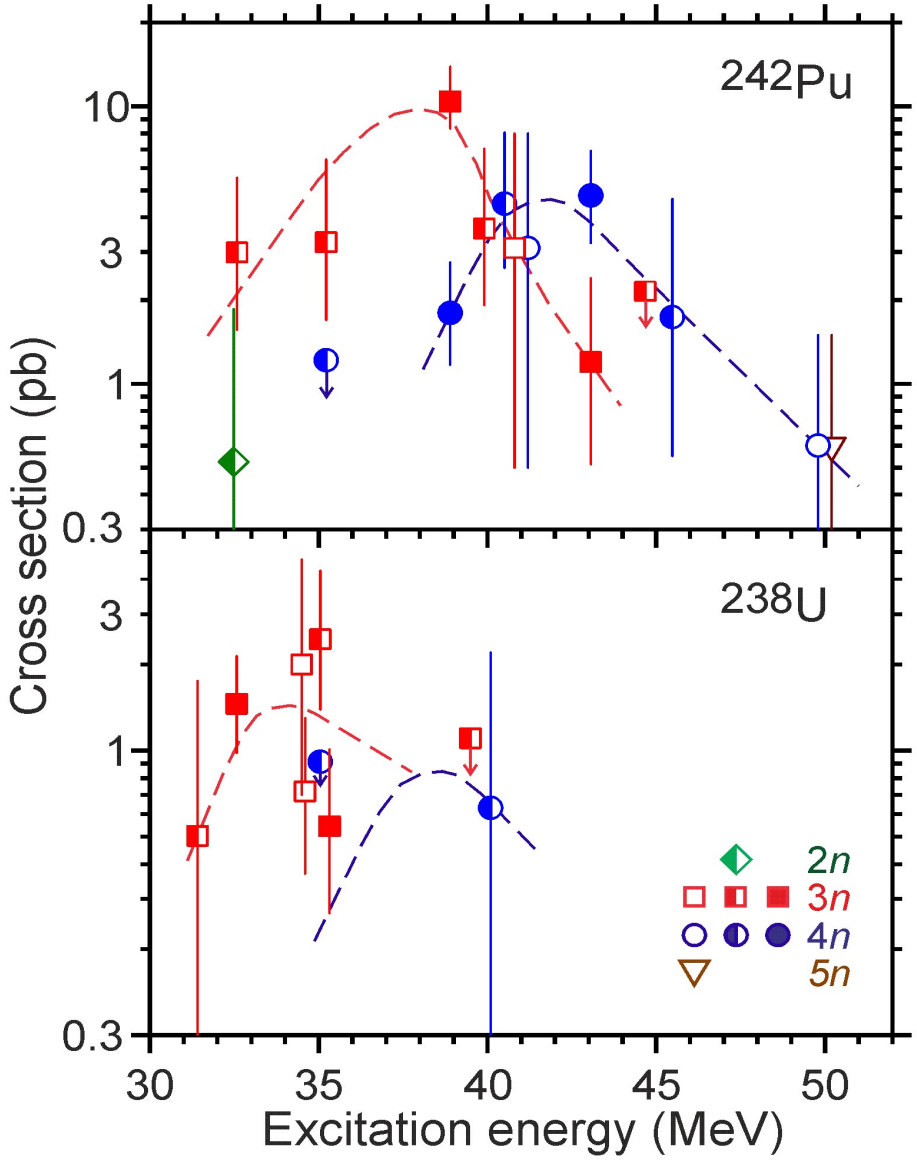


"experiment":
E_{2+} = 100 - 200 keV
0^+: 82% and 2^+: 18%

two-center shell model: β_2 = 0.18, β_4 = -0.08
E_{2+} = 75 keV
0^+: 67% and 2^+: 33%

deduced for 0^+: 82% and 2^+: 18%
β_2 = 0.13
E_{2+} = 101 keV

E.A. Kolganova



Excitation functions

^{242}Pu(^{48}Ca,3-4n)^{286,287}Fl

94 new events

^{238}U(^{48}Ca, 3n)^{283}Cn

16 new decay chains

Summary of experiments @ Superheavy Element Factory in 2021-2022

Beam time in 2021: 5095 h

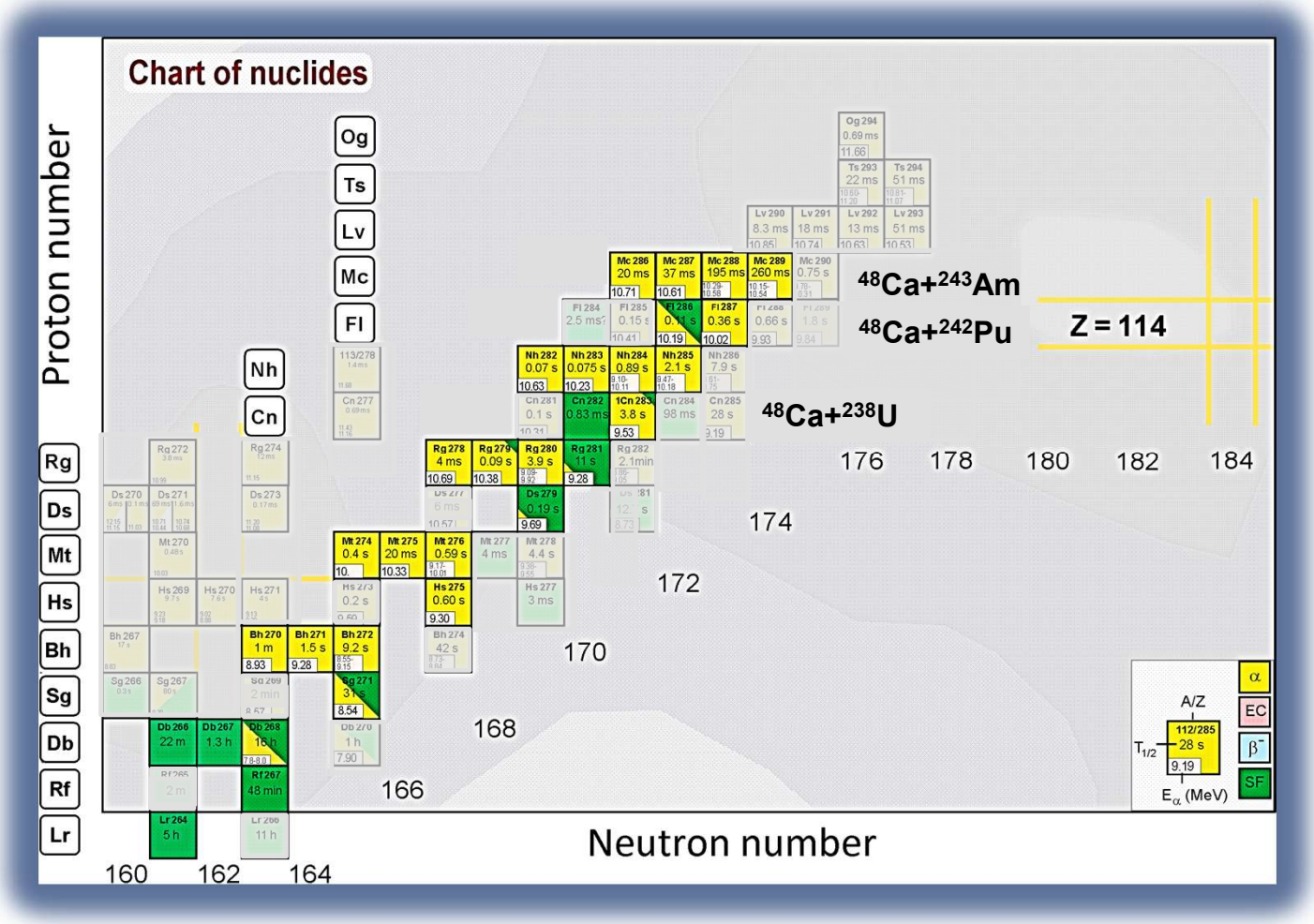
Experiments:

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

$^{242}Pu + {}^{48}Ca \rightarrow {}^{290}Fl^*$

$^{238}U + {}^{48}Ca \rightarrow {}^{286}Cn^*$

- 235 new events of synthesis of superheavy nuclides;
- Decay properties 30 isotopes;
- New isotopes: ^{287}Mc, ^{264}Lr;
- New decay modes: ^{268}Db (alpha-decay), ^{279}Rg (spontaneous fission);
- Indication of excited state in ^{286}Fl;
- Test of target stability up to 6.5 pμA of ^{48}Ca;



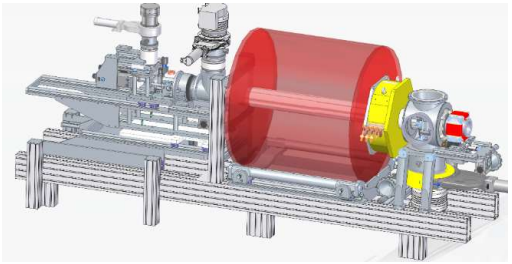
Synthesis of new elements @ SHE Factory

TARGETS

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

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

BEAMS



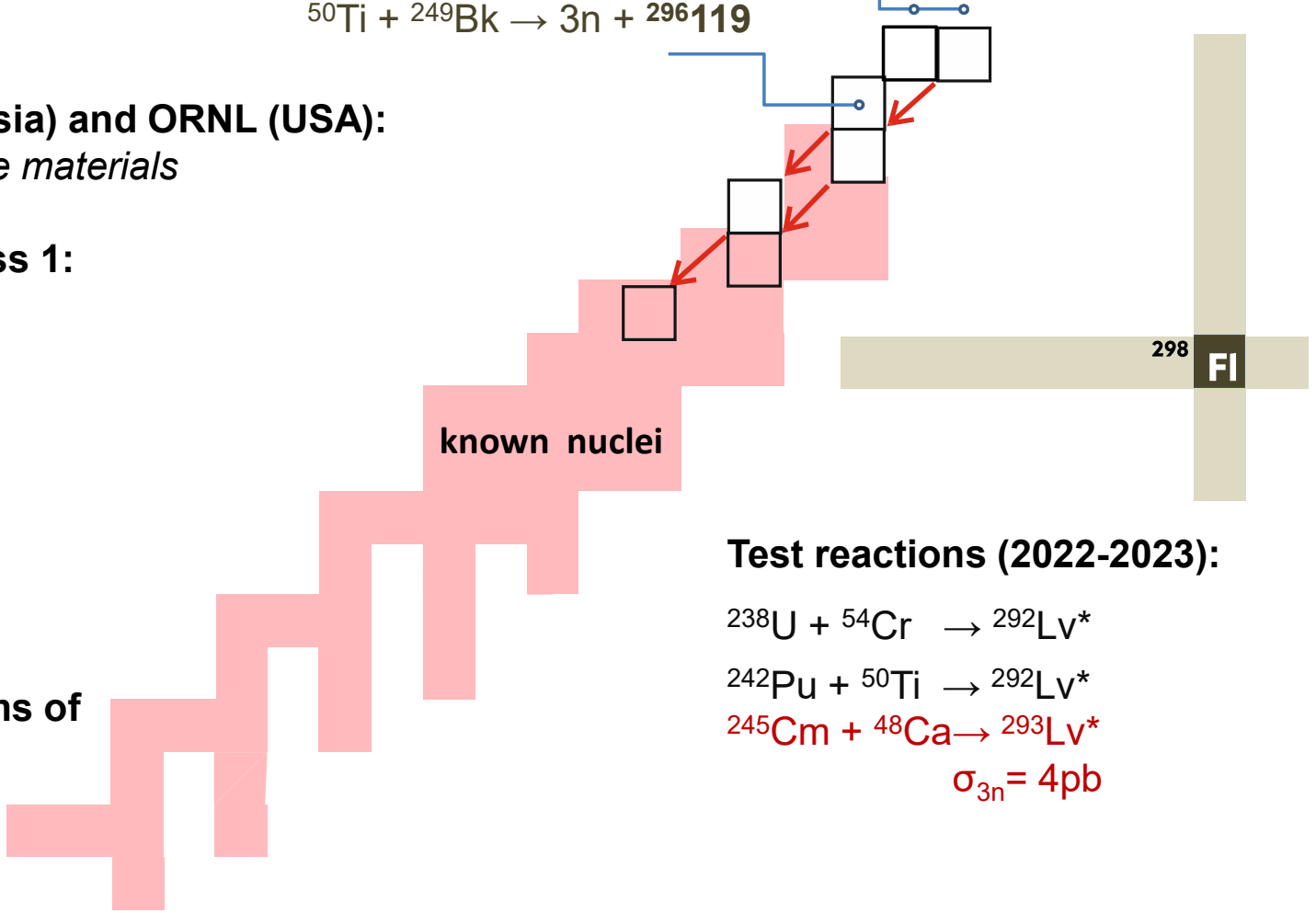
- **Production of high-intensity beams of ^{50}Ti, ^{54}Cr and others**

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

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

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

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



Test reactions (2022-2023):

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

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

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

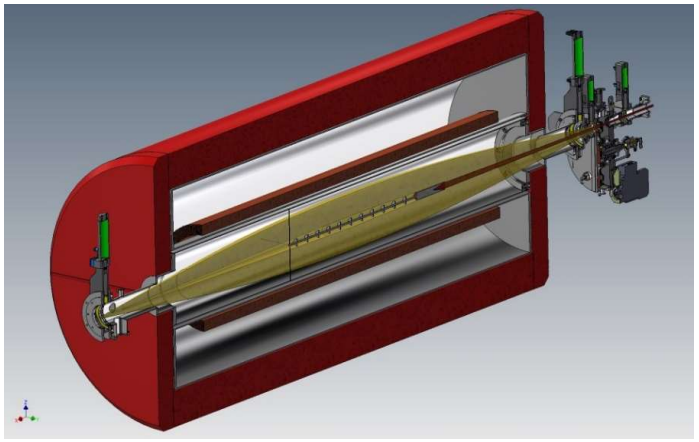
σ_{3n}= 4pb

SHE research program with existing separators @ SHE Factory

- Spectroscopy of SHE;
- Chemical studies for SH nuclei with half-lives **longer than 1 sec** (114 and lighter);
- Precise mass measurements (new developments are due);

- Synthesis of new SHE;
- Synthesis of new neutron-deficient isotopes of SHE: “shaping” of island of stability;
- Search for rear decay channels in ^{48}Ca-induced reactions (EC, pxn, 1-2n): towards island of stability;
- Decay modes, excitation functions, etc.

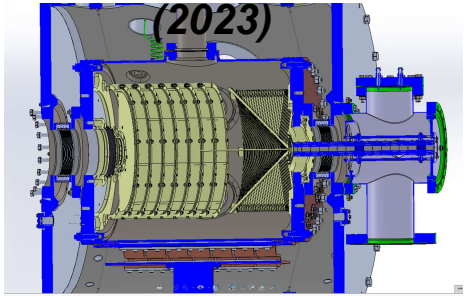
R&D and launch of new experimental setups at SHE Factory



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 element 117)*

Gas catcher (2023)



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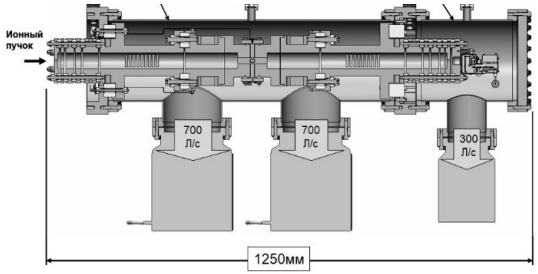
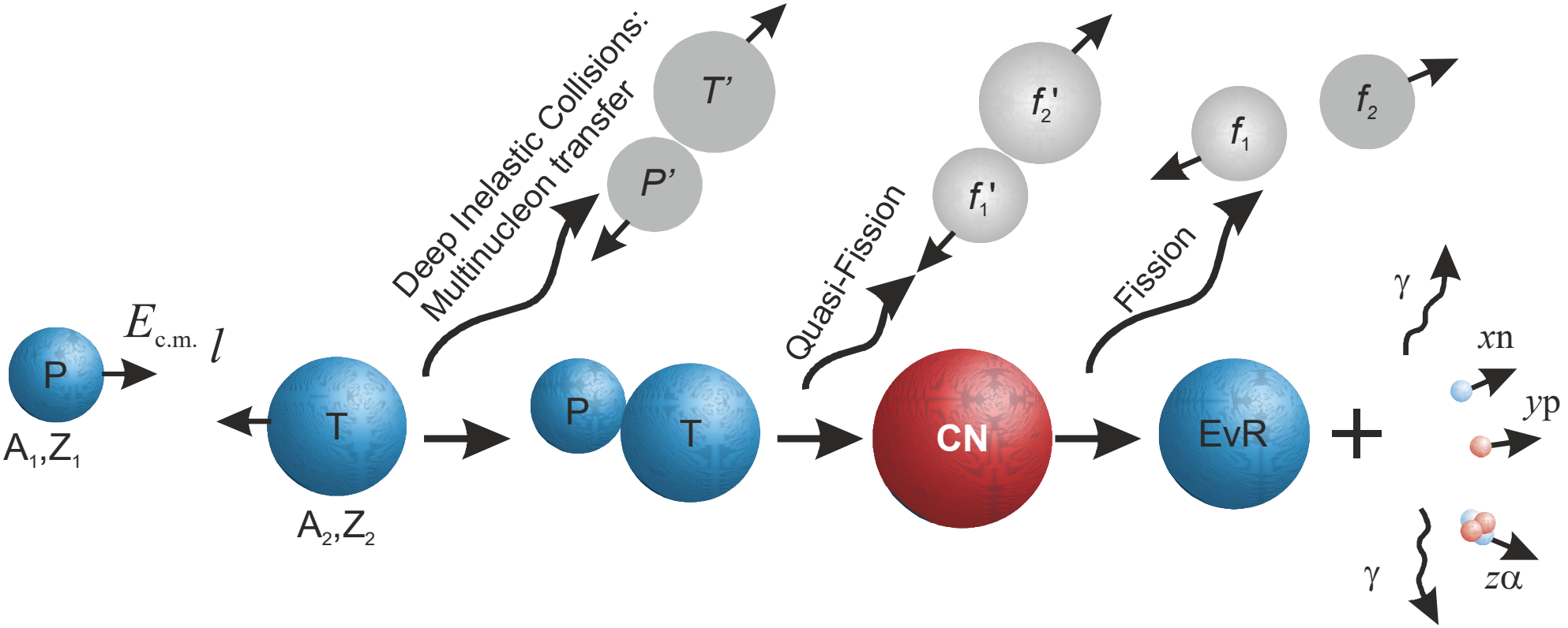
MR-TOF-MS (2025)

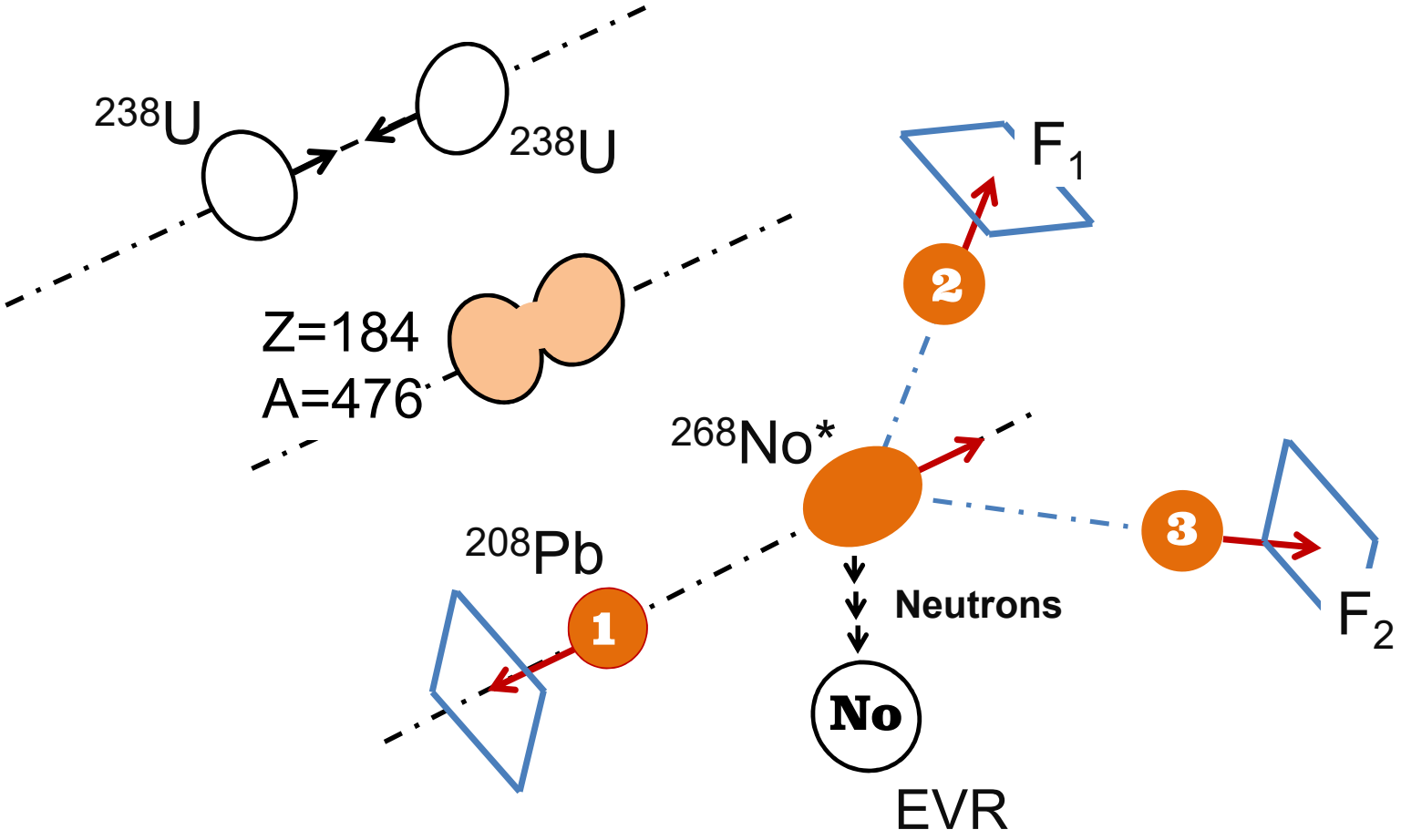


Mass-spectrometry of SHE: $\Delta M / M \sim 10^{-7}$

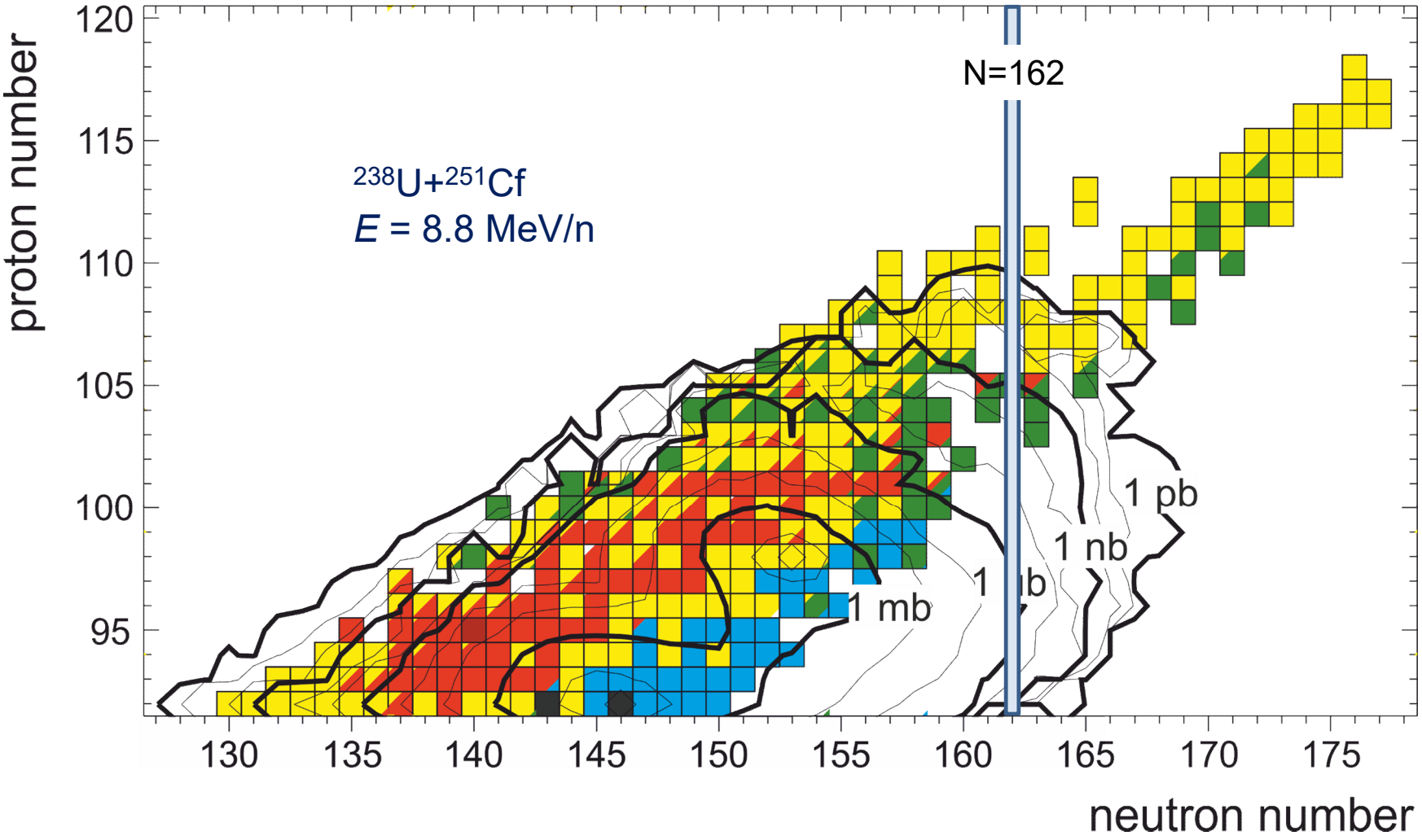
Other developments under consideration:
Laser spectroscopy; Penning trap setup; etc.


P
$E_{c.m.}$ l
A_1,Z_1
T
A_2,Z_2
Deep Inelastic Collisions:
Multinucleon transfer
T'
P'
P
T
Quasi-Fission
f_2'
f_1'
CN
Fission
f_1
f_2
EvR
+
γ
xn
yp
γ
zα

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



slide by Yu. Oganessian


proton number
neutron number
120
115
110
105
100
95
130
135
140
145
150
155
160
165
170
175
N=162
^{238}U+^{251}Cf
E = 8.8 MeV/n
1 pb
1 nb
1 mb

V.V. Saiko

Thank you for your attention