

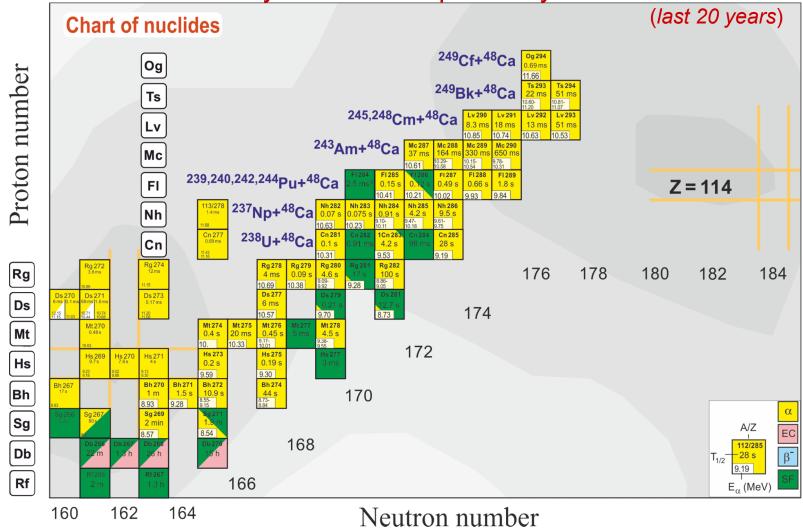
# Superheavy elements at SHE Factory recent achievements and perspectives

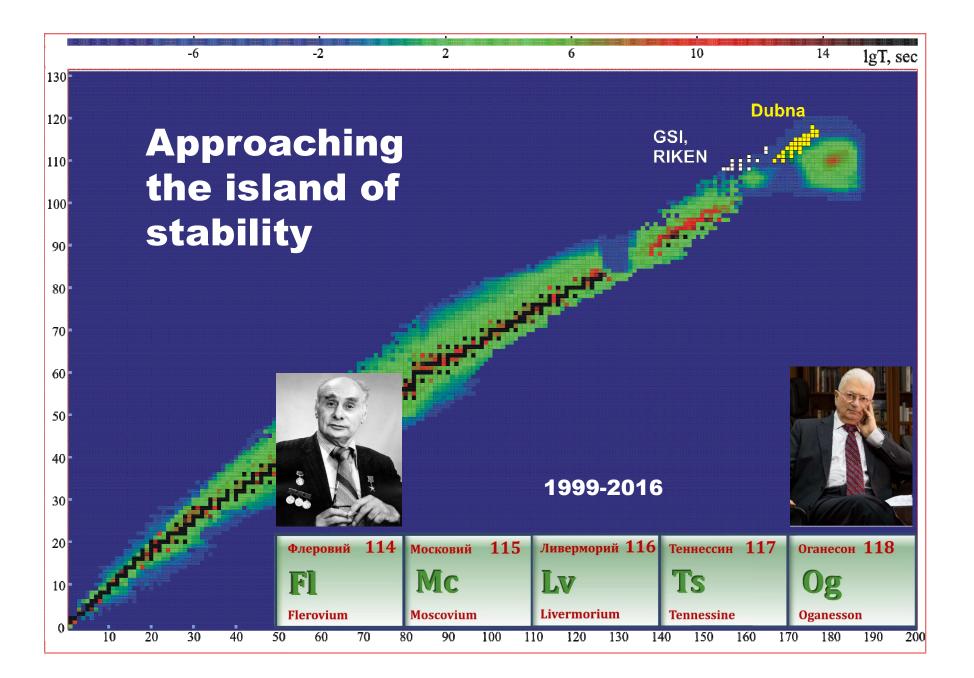
Alexander Karpov Flerov Laboratory of Nuclear Reactions, JINR

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

### **GREAT PROGRESS**

in Synthesis of Superheavy Nuclei







### 10 of 18 elements discovered since 1956 were first synthesized in Dubna

цезий 2	55 (s	Барий	50 %	Лантан	57'S	Тафний	12 30'55'	Тантал /	' <sup>3</sup> N'6'	Больфрам	14 16	Рений	13.6	Осмий	70 <sub>50</sub> '65'	Иридий //	. Платия	a /0 <sub>50%</sub>	Залото	19,51'66'	Ртуть	80 <sub>50'65</sub>	Таллия	01 <sub>%</sub>	свинец	04 <sub>m</sub>	Висмут	03 <sub>śp</sub> :	Полоний	04 <sub>ie</sub>	Actar 6	5 fix	Радон	50
Cs	1,89306	Ba	5.2   76 3510	La	5,57%) 9149	Hf	6(83507 12310	Та	7.98	W	7.68 19320	Re	7,85 21,530	Os	8.7 Z2450	Ir a	Pt	9.0 21450	Au	9,22567 19310	Hg	10.43750 13546,3	Tl	5,10525 850-	Pb	7/1665 11359	Bi	7,289 9320	Po	8,41671 9430	At	9,0	Rn	20,71890 9,73
132,90543 Cesium	23.44 971	137,327 Barium		139,9055 Lanthanum	920 3454	178,40 Hafnium		180,0470 Tantalum		183,84 Tungsten	1420 5075	186,207 Rhenium	2186 2596	190,23 Osmium	3053 2012	192,22 34 Iridium -4	4: 195,08 3s Platinu	17/8.4 n 7/520	196,96654 Gold	064, 8 2859	200,59 Mercury	-33.62 326,77	204,3833 Thallium	384 471	207,2 Lead	327.46 1749	208,98037 Bismuth	771-1 1564	[209] Polonium	254 952	[210] Astatine	302 317	[222] Radon	-71 -61.7
Франций 🕴	87	Радий	88	Актиний	89 <sub>01'5'</sub>	Резерфорд	unii 104	дубний 1	05	Сиборгий 1	06	Борий 1	07	Хассий	108	Мейтнерий 10	Э Дармин	адтий 110	Рентрений	111	Консранки	ий 112	Нихоний	113	Флеровий	114	Масковий	115	Ливерморн	u 116	Тениессин	117 0	Оганесон 1	.18
These	4,073	Ra	5,27892	Ac	5, 7	Rf	oJ Lo	Db	60	Sg	68	Bh	68	Hs	br"	Mt '	Ds	68	Rg	66*	Cn		Nh		FI		Mc		Lv		Te		0g	
Fr		na	5000	AL	10050			[262] Dubnium		[266] Seaborgium	_	DII				INTC	103		1.6		UII		TATE				1.11.0	_	1 PA		1.0			

Лантаноиды Lanthanoides

Церий	58 <sub>41'84</sub>	Празеодим 59																			Тулий	69 <sub>c</sub>	Иттербий	70	Лютеций	71
Се	5,5387 6770	Pr /	Nd	3,525 7305	Pm	2.35 726-	Sm	5,6437 7520	Eu	5.6791 5244	Gd	6.159 3501	Tb	5,8679 \$230	Dy	3.9389 8551	Но	5.02 S 8005	Er	6,1038 9866	Tm	6.18/31 9321	Yb	6.254 G 6965	Lu	5,42585 984
140,115 Cerium	7 <i>10</i> 3424	140,90765 Praseodymium 3	144,24 Neodymiu	iaire 1017 - 1017	[145] Promethium	1042 3000	150,36 Samarium	1023. 1759	151,965 Europium	822 596	157,25 Gadolinium	1914 3364	158,92534 Terbium	1 899 3221	162,50 Dysprosium	1411 3561	164,93032 Holmium	147.2 2694	167,26 Erbium	1579 2683	168,93421 Thulium	105 1946	173,04 Ytterbium	824 194	174,967 Lutetium	1662 3392

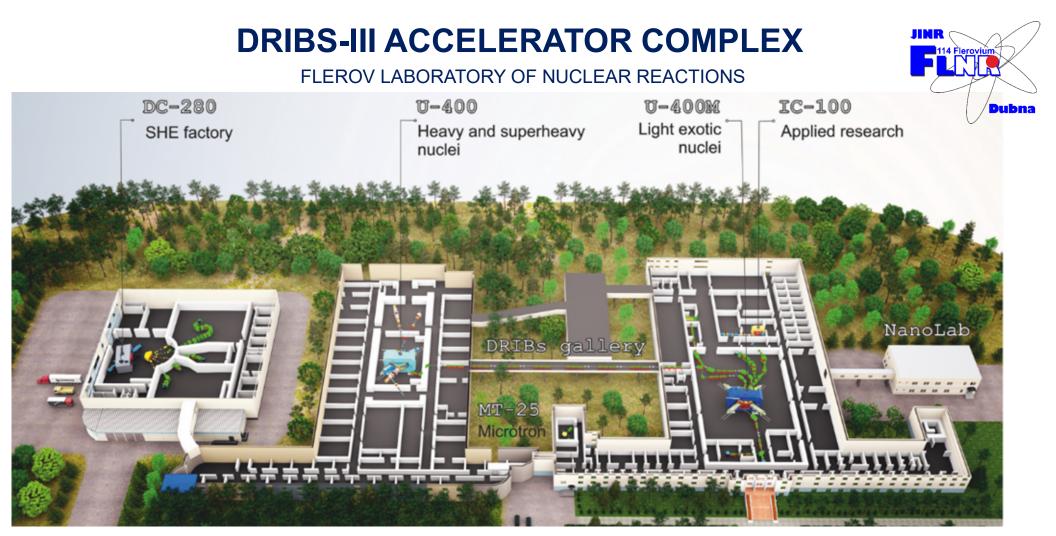
#### Актиноиды Actinoides

Торий	90 <sub>5%</sub>	Протактиний9	1 <sub></sub>	Уран	92 <sub>5.160</sub>	Нептуний 9	3 <sub>51'61</sub>	Плутоний	94 <sub>sc</sub>	Америций 9	5 <sub>11</sub>	Кюрий	96 <sub>scor</sub>	Берклий	97 <sub>s:</sub>	Калифорний98	8 <sub>30</sub> *	эйнштейний <b>99</b> <sub>31</sub>	ф	ермий 100	менлелевий101	ar	Нобелий 102 <sub>зб</sub>	Лоурен	ск <b>й</b> 103	e.
Th					6.19403 18850	Np	6.2657 20258	Pu	6.05 19540	Am	5,997 13670	Cm	6,82 4510							Fm			No 645	Lr		-
232,0381 Thorium	1750 4799	231,03588 Protactinium	1572	238,0289 Uranium	1135 4131	[237] Neptunium	644 7930	[244] Plutonium	740 3328	[243] Americium	1136 2007	[247] Curium	1345	[247] Berkelium	1053	[251] Californium	900	[252] 860 Einsteinium -		257] ermium	[258] S2 Mendelevium	27	[259] \$27 Nobelium	[262] Lawren	icium	1627

Водород	1
H	13 59844 0.0599
1,00794 Hydrogen	-259.34

H - curato, / symbol 1.00794 - arounes wacca / atomic mass 131 - Joneryonian kon-phirypauus / electron configuration 13.59844 - 1-in norenupa konkrauw, 80 / 1st ionization potential, eV 0.0689 - northoren, W / M / density, kg // m -259.34 - rewineparypa nonaewen, ®C / beints temporature, ®C -52.87 - rewineparypa nonaewen, ®C / beints temporature, ®C

Kr



#### FLNR's basic directions of research:

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

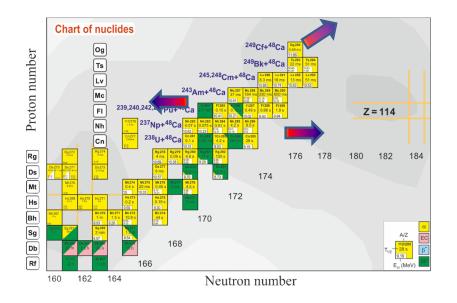
### SHE research: Main tasks

Experiments at the extremely low ( $\sigma$ <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 <sup>48</sup>Ca @ DC-280:

- Intensity: up to  $6 \cdot 10^{13}$  ions/s,  $10 p \mu A$
- Energy: 5 8 A·MeV
- Efficiency: ~50%

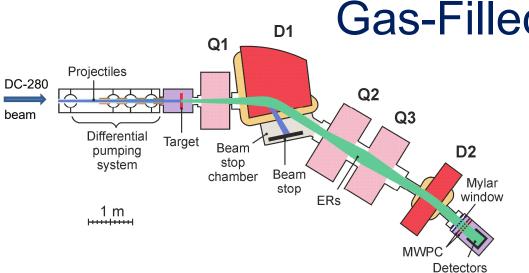


### **Cyclotron DC-280 Factory of superheavy elements**

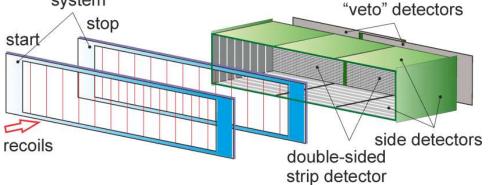
Beam of <sup>48</sup>Ca

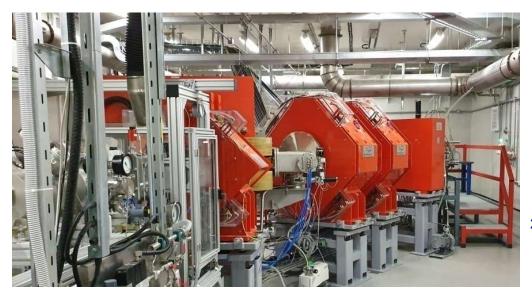
Achieved Intensity: 4.3.10<sup>13</sup> ions/s

Efficiency: ~50%



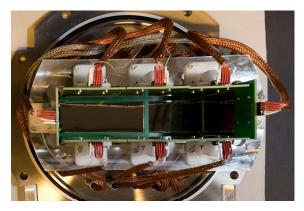
# Gas-Filled Separator, DGFRS-2







<sup>242</sup>Pu 24-cm target wheel 12 sectors



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

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

~60 days

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

# Results of the first experiment <sup>243</sup>Am + <sup>48</sup>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 pxn channel
- EC branch for <sup>288</sup>Mc and <sup>284</sup>Nh

 $I = 1.2-1.3 \text{ p}\mu\text{A} \sim (7-8) \cdot 10^{12} \text{ ions/s}$ 

# **Transmission**

- From <sup>206</sup>Pb(<sup>48</sup>Ca,2n)<sup>252</sup>No test reaction: 55±7%
- From <sup>243</sup>Am(<sup>48</sup>Ca,2-3n)<sup>288,289</sup>Mc reaction:

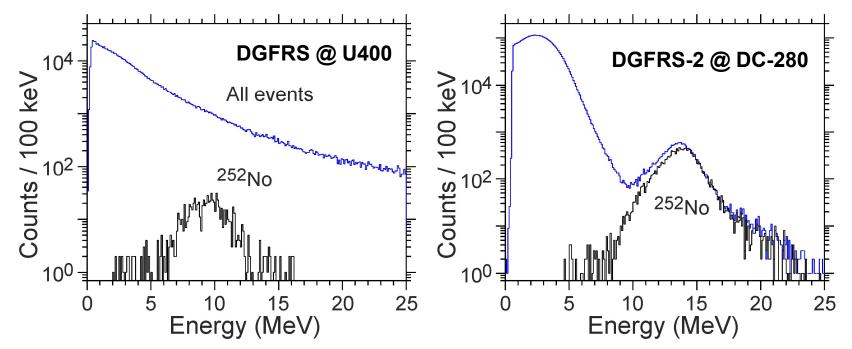
### Comparison of results at the same <sup>48</sup>Ca energy

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

## **Background conditions**

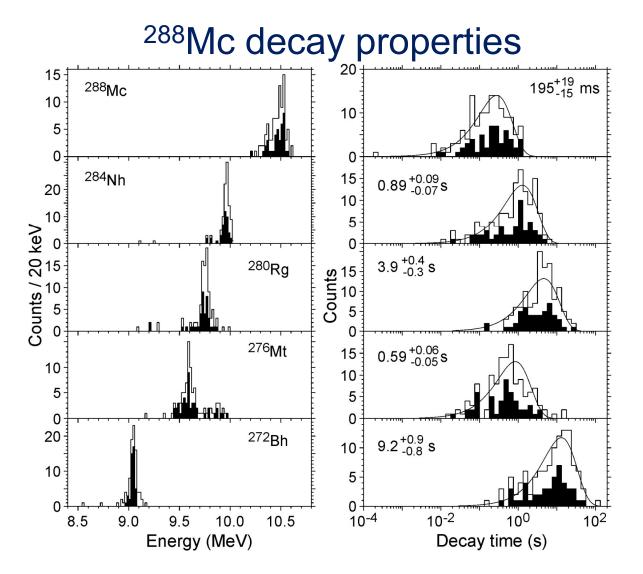
### <sup>206</sup>Pb+<sup>48</sup>Ca $\rightarrow$ <sup>252</sup>No+2n (Cross section 0.5 mb)

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 <sup>252</sup>No (bottom black line) nuclei produced in the <sup>206</sup>Pb(<sup>48</sup>Ca,2*n*) reaction using separators DGFRS (a) and DGFRS-2 (b).

### **Results of the first experiment**

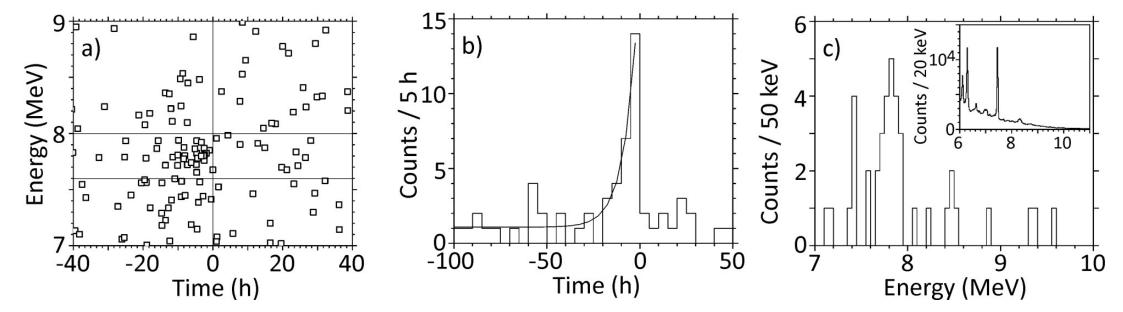


DGFRS, JINR TASCA, GSI BGS, LBNL

**DGFRS-2, JINR** 

# First observation of α-decay of <sup>268</sup>Db and new isotope <sup>264</sup>Lr

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

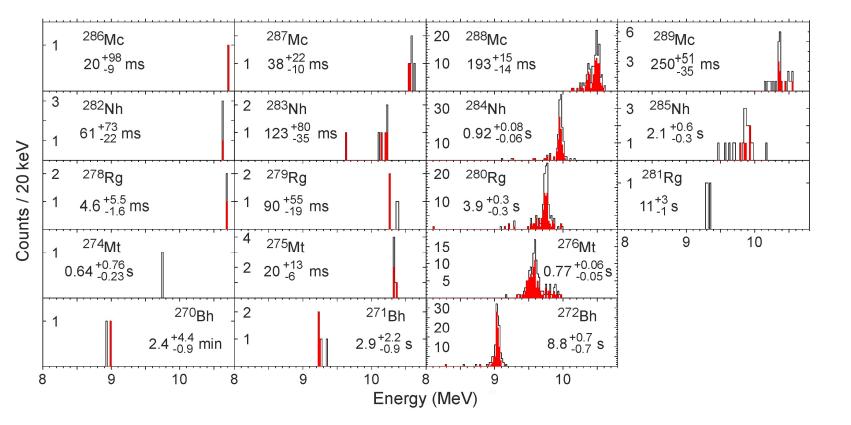


# First experiments: statistics summary

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

### <sup>243</sup>Am(<sup>48</sup>Ca,2-5n)<sup>286-289</sup>Mc Reaction

### 125 decay chains Decay properties of 22 isotopes

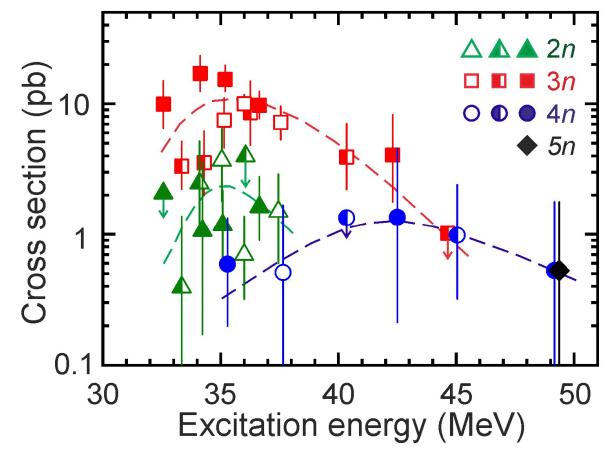


DGFRS, JINR TASCA, GSI BGS, LBNL

**DGFRS-2, JINR** 

# **Results of the first experiments** Excitation function

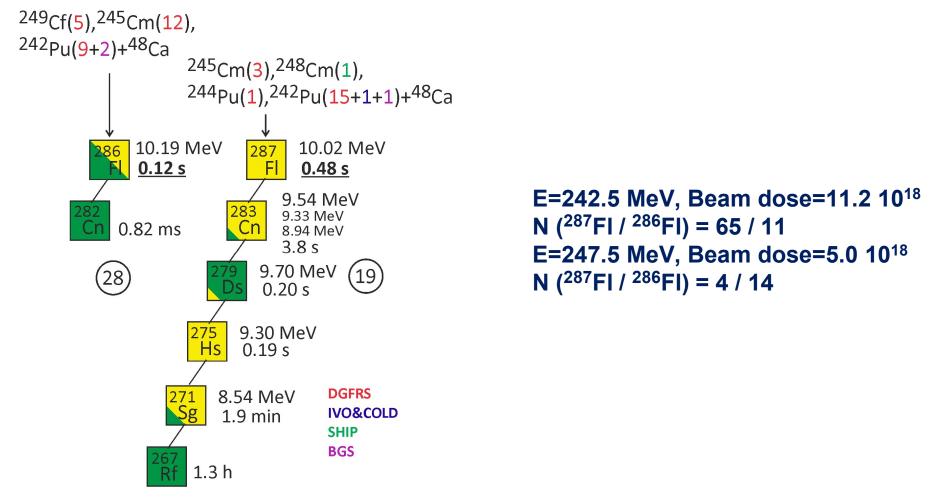
DGFRS (open), TASCA (half open), DGFRS-2 (filled)



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

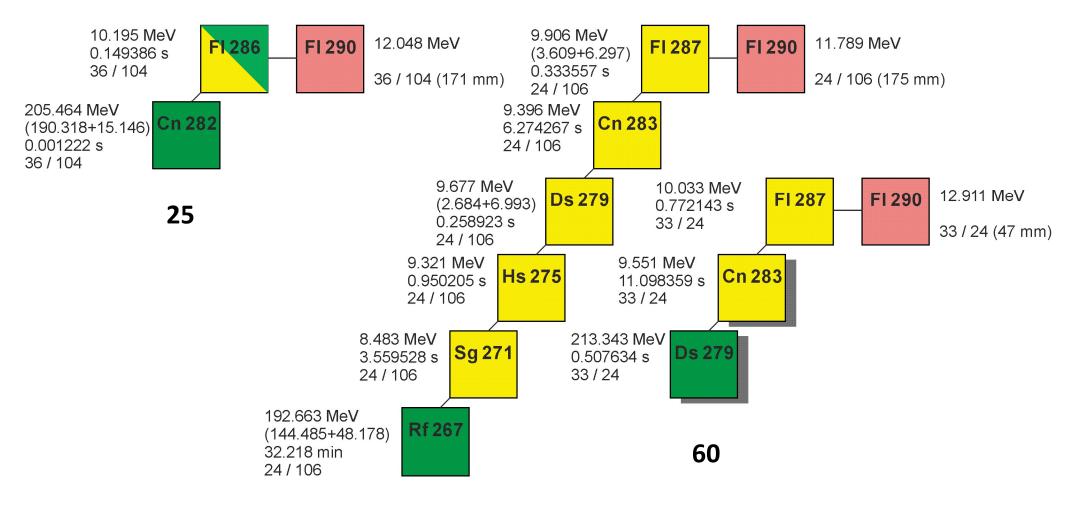
Completed in June 2021

#### **Preparation of experiment on chemistry of FI and Cn** Results of the experiment <sup>242</sup>Pu+<sup>48</sup>Ca



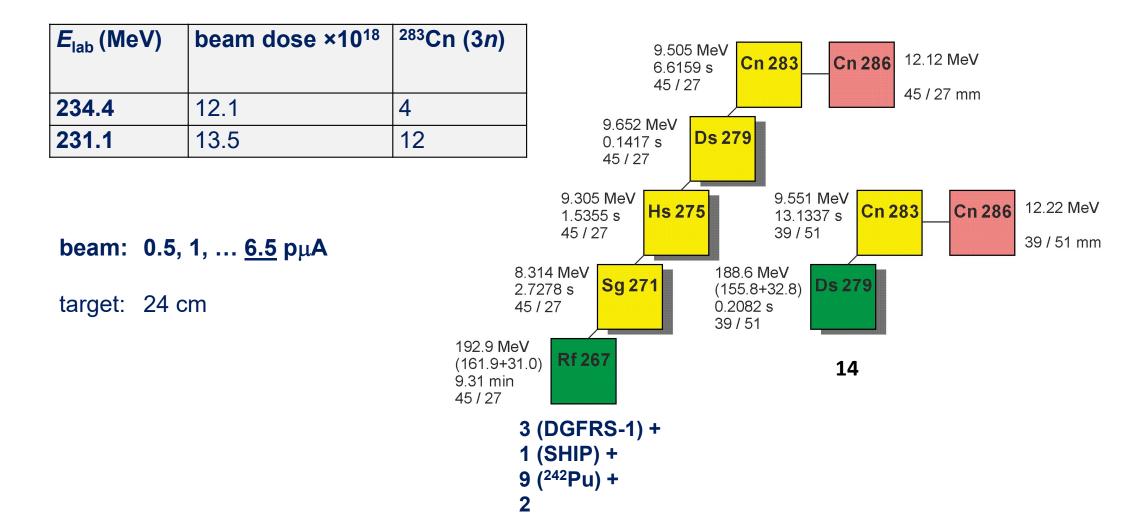
I = 0.05, 0.1 ... 1, 1.5, 2.0, 2.5, 3 pμA

### Results of the first experiment <sup>242</sup>Pu+<sup>48</sup>Ca



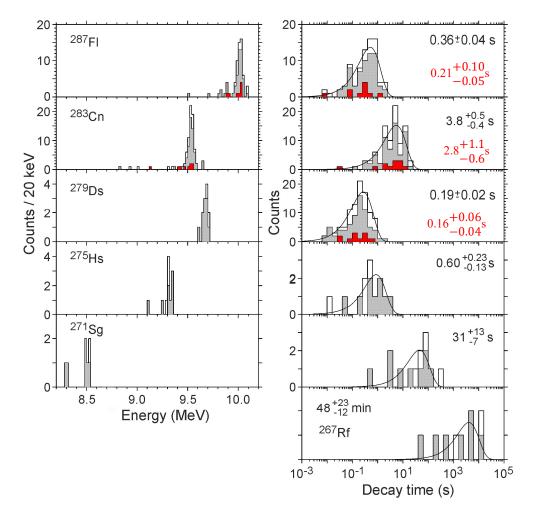
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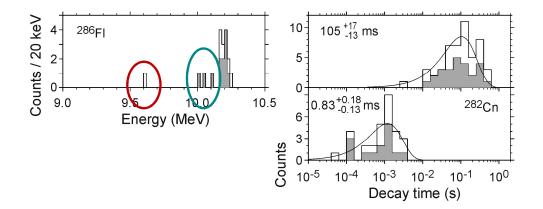
### <sup>238</sup>U(<sup>48</sup>Ca,3n)<sup>283</sup>Cn (September – October 2021)



### <sup>242</sup>Pu(<sup>48</sup>Ca,3-4n)<sup>286,287</sup>FI and <sup>238</sup>U(<sup>48</sup>Ca,3n)<sup>283</sup>Cn

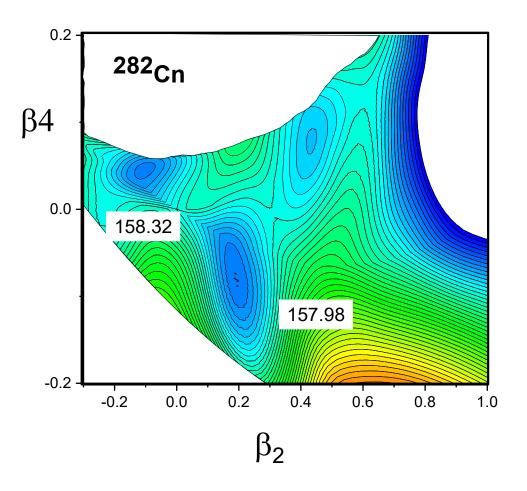
#### Decay properties of 8 isotopes





- <sup>287</sup>FI, <sup>283</sup>Cn, and <sup>279</sup>Ds: decay through different states
- 286 FI: α-decay line 9.6 MeV for was not observed
  A. Såmark-Roth et al., PRL (2021)
- <sup>286</sup>FI: decay on 2<sup>+</sup> rotational state <sup>282</sup>Cn or through isomeric states

#### Presumable $\alpha$ -decay of <sup>286</sup>Fl on rotational 2<sup>+</sup>-state of <sup>282</sup>Cn

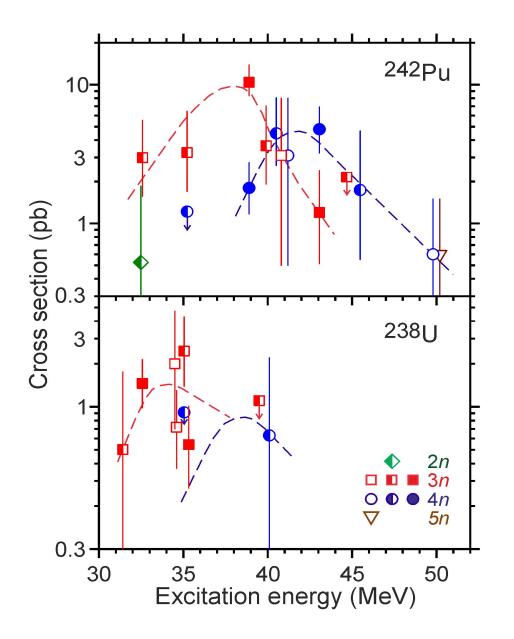


"experiment":  $E_{2+} = 100 - 200 \text{ keV}$ 0<sup>+</sup>: 82% and 2<sup>+</sup>: 18%

*two-center shell model:*  $\beta_2 = 0.18$ ,  $\beta_4 = -0.08$  $E_{2+} = 75$  keV 0<sup>+</sup>: 67% and 2<sup>+</sup>: 33%

deduced for 0<sup>+</sup>: 82% and 2<sup>+</sup>: 18%  $\beta_2 = 0.13$  $E_{2+} = 101 \text{ keV}$ 

E.A. Kolganova



### **Excitation functions**

<sup>242</sup>Pu(<sup>48</sup>Ca,3-4n)<sup>286,287</sup>Fl 94 new events

<sup>238</sup>U(<sup>48</sup>Ca, 3n)<sup>283</sup>Cn 16 new decay chains

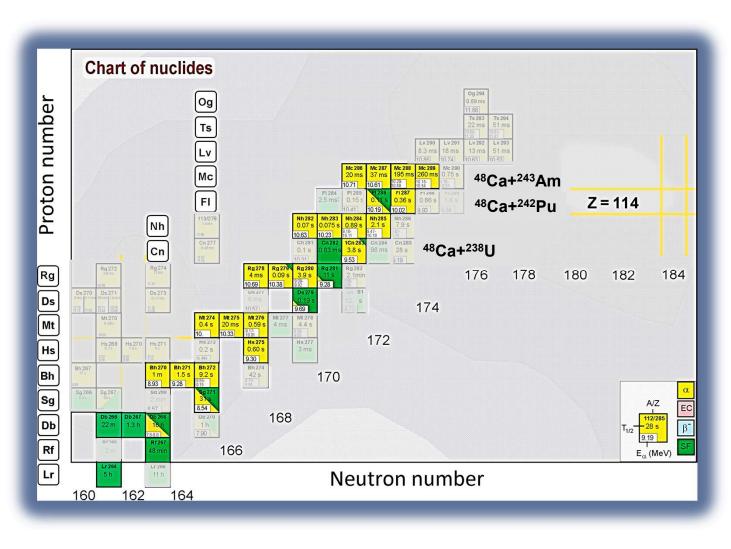
#### Summary of experiments @ Superheavy Element Factory in 2021-2022

#### **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: <sup>287</sup>Mc, <sup>264</sup>Lr;
- New decay modes: <sup>268</sup>Db (alphadecay), <sup>279</sup>Rg (spontaneous fission);
- Indication of excited state in <sup>286</sup>FI;
- Test of target stability up to 6.5 pµA of <sup>48</sup>Ca;

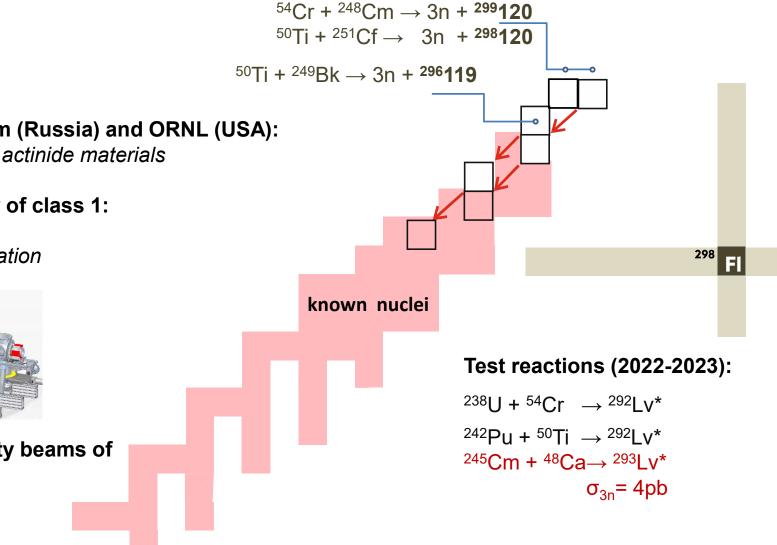
#### Beam time in 2021: 5095 h



#### TARGETS

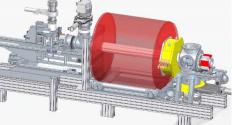


### Synthesis of new elements @ SHE Factory



- 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 <sup>50</sup>Ti, <sup>54</sup>Cr and others
- New ECR-28 GHz (2024)

### SHE research program with existing separators @ SHE Factory

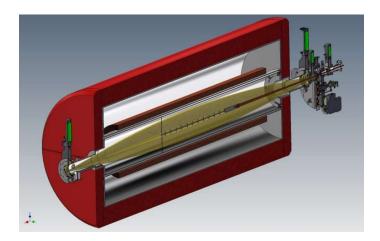


- Spectroscopy of SHE;
- Chemical studies for SH nuclei with half-lives longer than 1 sec (114 and lighter);
- Precise mass measurements (new developments are due);



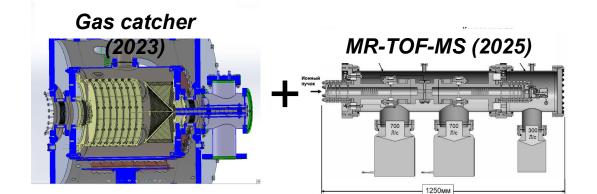
- Synthesis of new SHE;
- Synthesis of new neutron-deficient isotopes of SHE: "shaping" of island of stability;
- Search for rear decay channels in <sup>48</sup>Ca-induced reactions (EC, pxn, 1-2n): towards island of stability;
- Decay modes, excitation functions, etc.

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



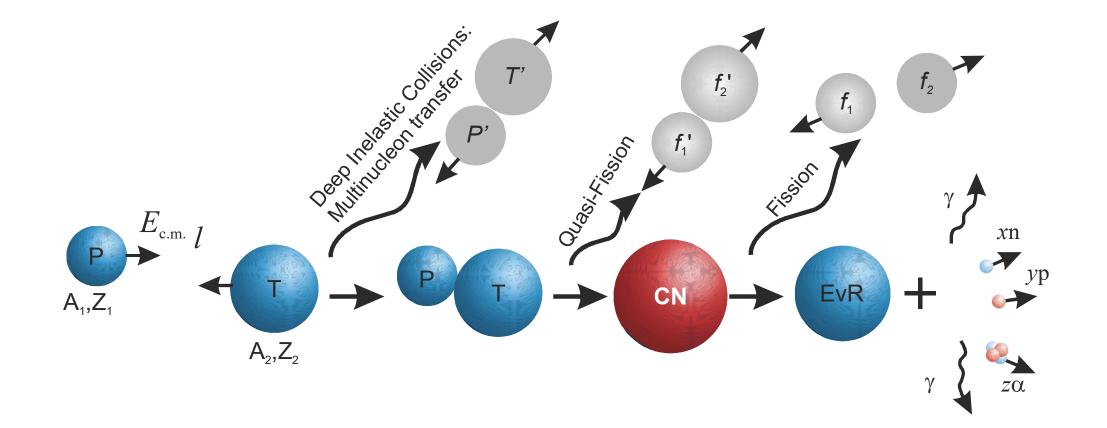
#### **GASSOL – Solenoid-based separator** (2025)

- Stopping SH atoms in a small volume of 1-2 cm<sup>3</sup>
- Chemistry of short-lived SHE T<sub>1/2</sub> ≥ 30 ms (up to element 117)

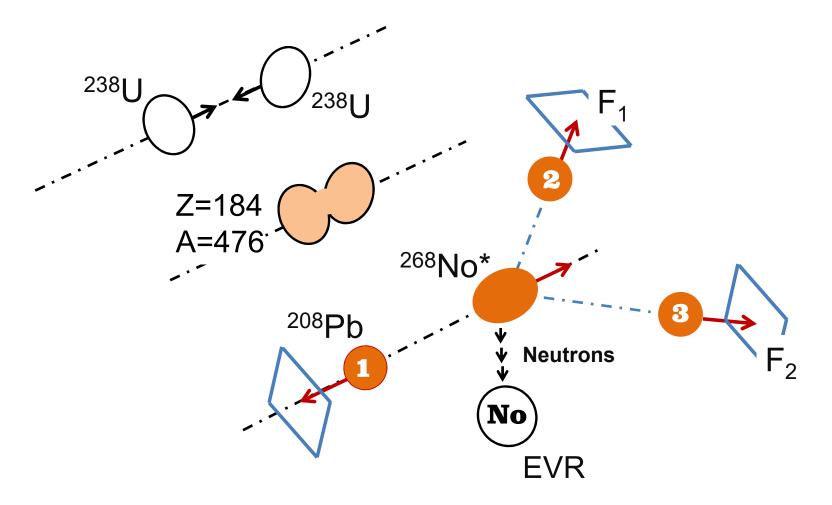


#### Mass-spectrometry of SHE: $\Delta M / M \sim 10^{-7}$

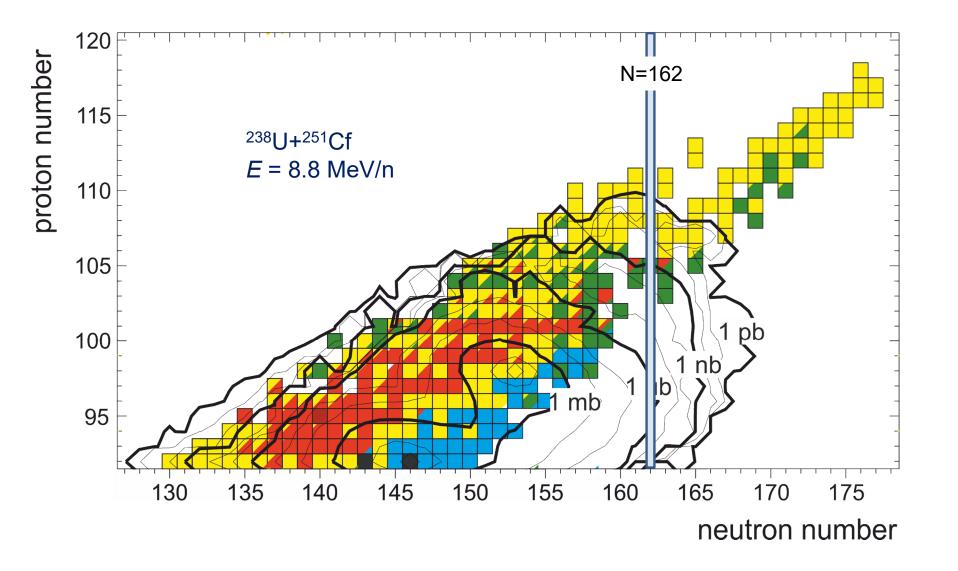
**Other developments under consideration**: Laser spectroscopy; Penning trap setup; etc.



### Studying the <sup>238</sup>U + <sup>238</sup>U reaction



slide by Yu. Oganessian



V.V. Saiko

### Thank you for your attention

