60th meeting of the PAC for Nuclear Physics

23-24 Jan 2025, JINR, Dubna

Study of chemical and physical properties of superheavy elements at the SHE Factory

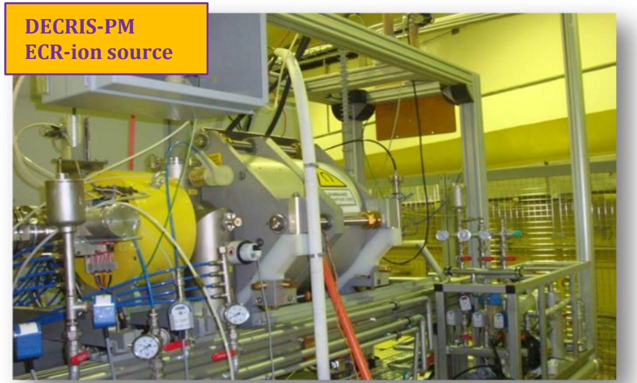
Alexandr Svirikhin

Head of sector №2

Flerov Laboratory of Nuclear Reactions

- **The gas-filled separator GRAND at the SHE Factory**
- **Experimental results obtained to date**
- **Chemistry of flerovium and copernicium**
- **Spectroscopy of SHE at GRAND**
- **Spontaneous fission properties of SHE**

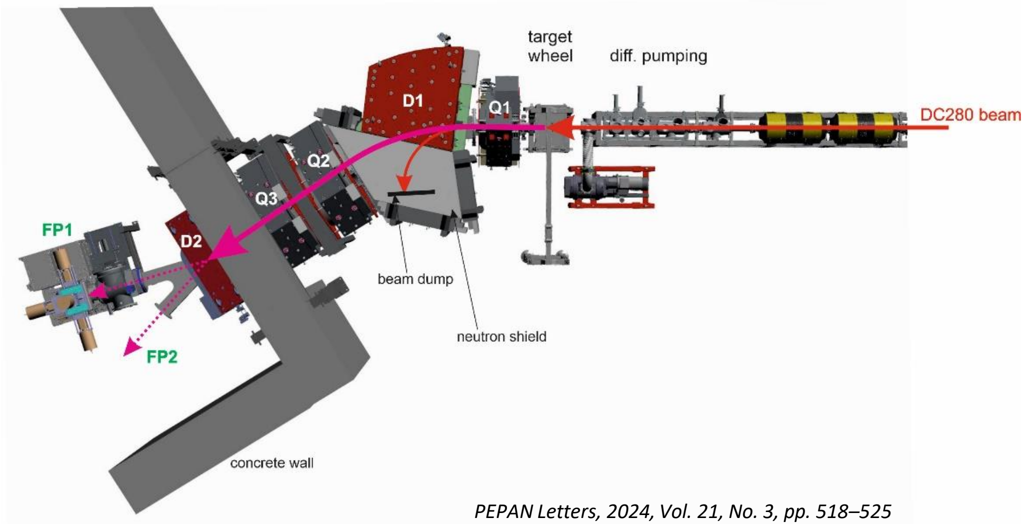
SHE Factory



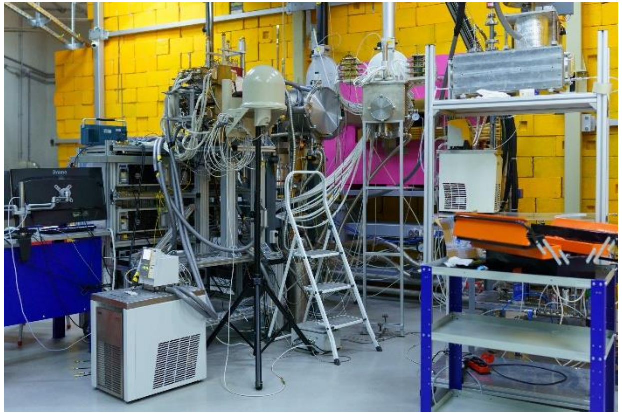
2024 beam program

Ion	Energy, MeV/nuclon	I (pμA)	I_{max} (pμA)	Setup
$^{40}Ar^{8+}$	231	1,9	1,9	GRAND
$^{48}Ca^{10+}$	225	2,0	2,0	GRAND
$^{54}Cr^{10+}$	306	2,0		DGFRS-2
$^{48}Ca^{10+}$	229	3,0	6,0	GRAND
$^{50}Ti^{9+}$	230	1,7	2,0	DGFRS-2
$^{50}Ti^{9+}$	280	1,7		DGFRS-2
$^{40}Ar^{8+}$	232	2,5		GRAND
$^{50}Ti^{9+}$	252	2,2	2,8	DC-280 group
$^{50}Ti^{9+}$	229	1,0		DGFRS-2
$^{50}Ti^{9+}$	275	1,7	1,9	DGFRS-2

Separator GRAND
Gas-filled Recoil Analyzer and Nuclei Detector



PEPAN Letters, 2024, Vol. 21, No. 3, pp. 518–525



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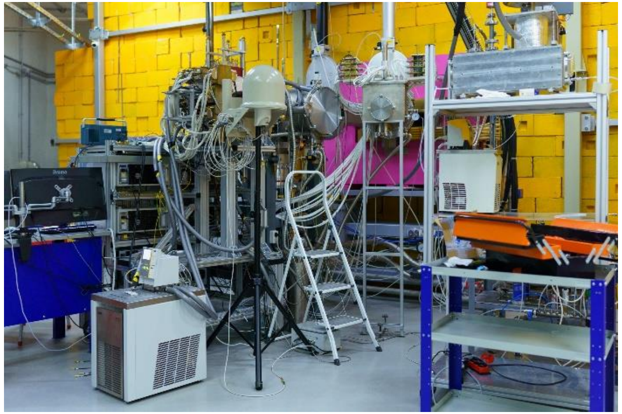

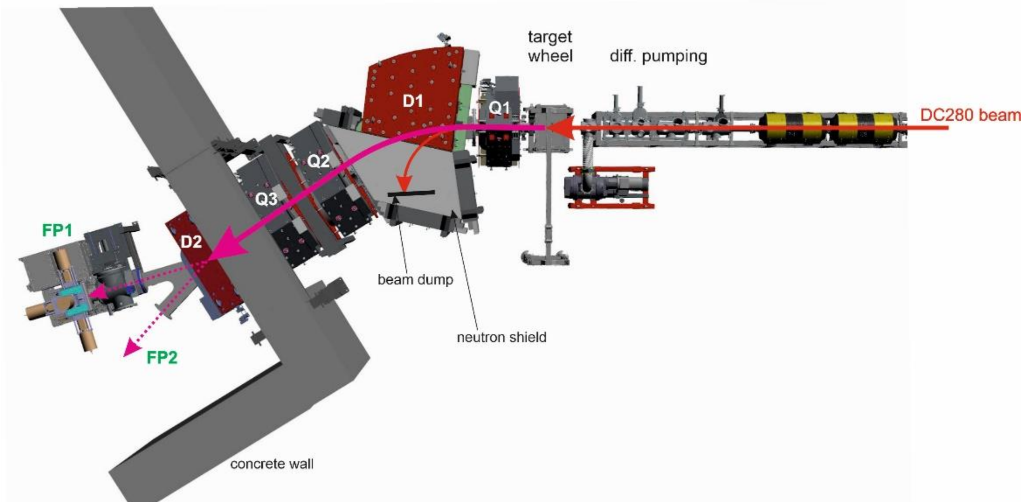

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Table 1. Comparative parameters of gas-filled separators used in experiments on the synthesis and study of the properties of isotopes of heavy elements

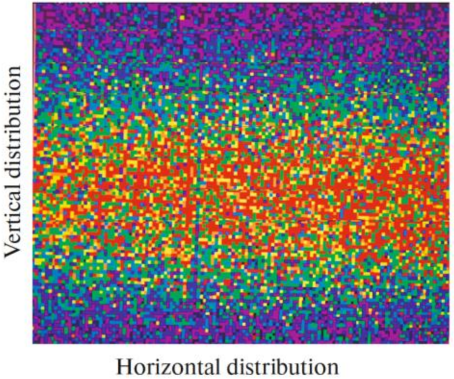
Facility	Configuration	Acceptance angle, msr	Rotation angle	Max. Bρ, T m	Dispersion mm/% Bρ	Length, m	Ref.
DGFRS1	$D_vQ_hQ_v$	10	23°	3.1	7.5	4.07	[5]
DGFRS2	$Q_vD_hQ_hQ_vD$	16	(32 + 10)°	3.35	32.8	7.41	[6]
BGS	Q_vD_hD	45	(25 + 45)°	2.5	20.0	4.6	[7]
GARIS1	$D_{vh}Q_hQ_vD$	12.2	(45 + 10)°	2.16	9.7	5.76	[8]
GARIS2	$Q_vD_hQ_hQ_vD$	18.5	(30 + 7)°	2.43	19.3	5.06	[9]
TASCA	DQ_hQ_v	13.3	30°	2.4	9.0	3.5	[10]
RITU	$Q_vDQ_hQ_v$	8.5	25°	2.2	10.0	4.8	[11]
SHANS	$Q_vDQ_vQ_h$	25	52°	2.88	7.3	6.5	[12]
SHANS2	$Q_vDQ_hQ_vD$	25	(30 + 10)°	2.56	20.9	5.97	[13]
AGFA	Q_vD_h	44–22[a]	38°	2.5		3.7–4.3[a]	[14]
GRAND	$Q_vD_hQ_vQ_hD$	16	(32 ± 15)°	3.35	32.8	7.95[b]; 6.84[c]	This work

[a] Distance to target up to Q 40 cm or 84 cm, [b] distance from the target to the "physical" focal detector, and [c] distance from the target to the "chemical" stop chamber of RNs.

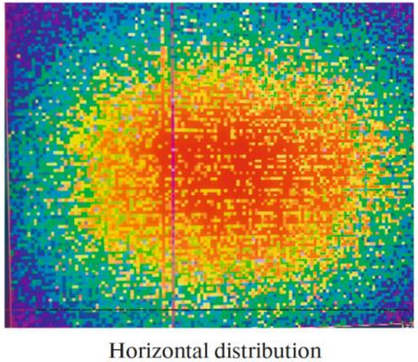
Tests of ion optics

$^{48}Ca + ^{170}Er \rightarrow 4n + ^{214}Ra$

FP1 – 100x100 cm^2 DSSD



$Q_v\ D_{30}\ Q_h\ Q_v\ D_{15}$



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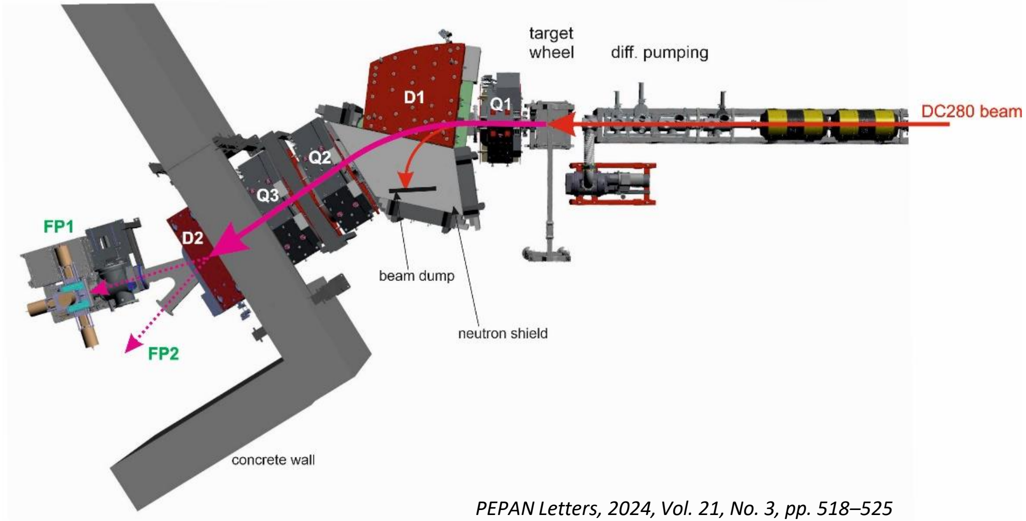
Separator GRAND

Gas-filled **R**ecoil **A**nalyzer and **N**uclei **D**etector



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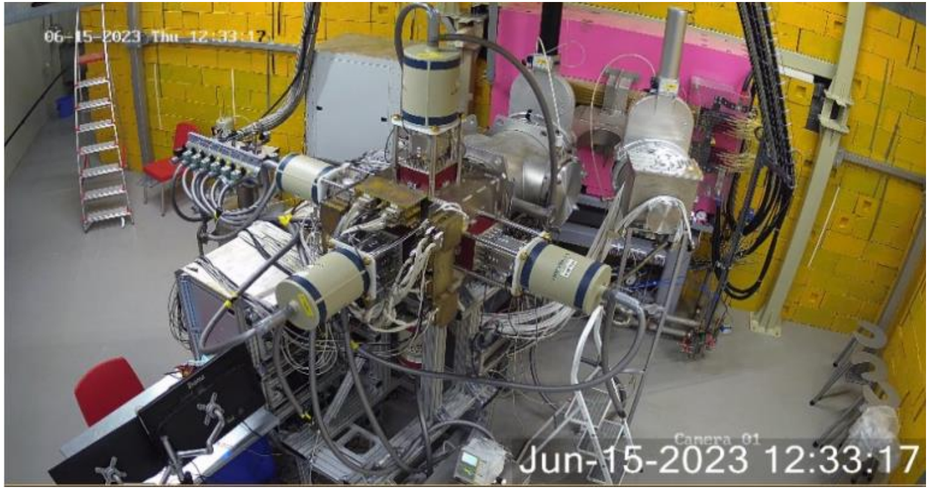
GABRIELA-III

Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

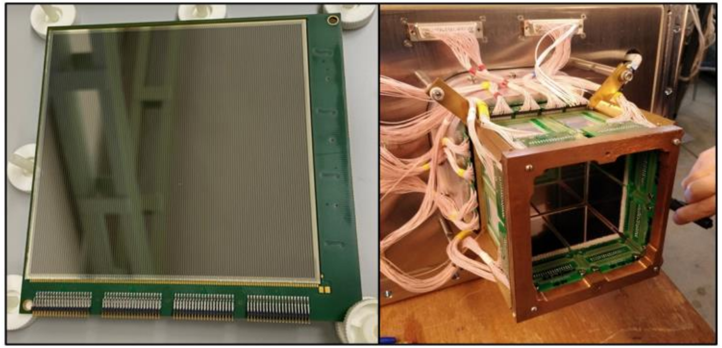


Si-detector (DSSSD)

- 100x100mm^2 or 128x128 strips
- 16384 pixels;
- Thickness: 500 µm

Tunnel Si-detectors (DSSSD)

- 50x60мм^2, 8 x 16x32 strips;
- Thickness: 700 µm



5 Ge-detectors

- Clover-type, HPGe,
- 100x100 mm, 70 mm height)
- BGO-shields

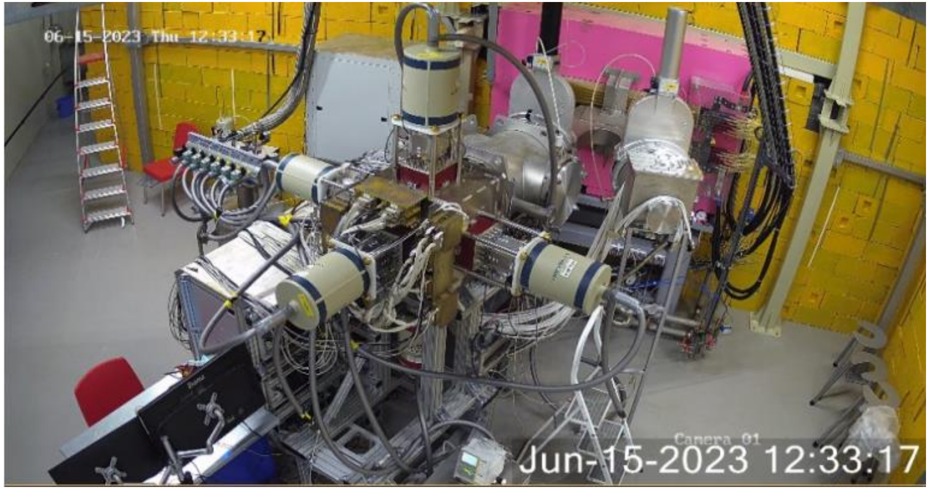
TOF system

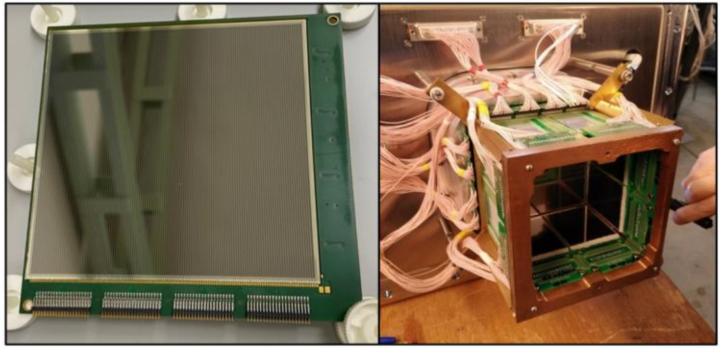
- 1 e-emitting foil
- 2MCP-based e-detectors (70x90 mm^2)

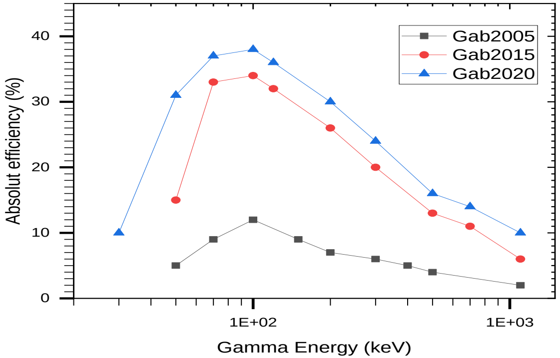
GABRIELA-III

Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

	FWHM, keV	Thresholds, keV
Focal plane 100x100mm^2	10.8±0.6 keV - 320 keV electrons; 16.5±0.8 keV - 7.92 MeV alphas	40-60
Tunnel Si-detectors	14.4±1.2 keV - 320 keV electrons 120±11 keV - 7.92 MeV alphas	60-100







Experimental results obtained to date

December 2022 - test experiment GRAND + GABRIELA focal plane (no HPGe)

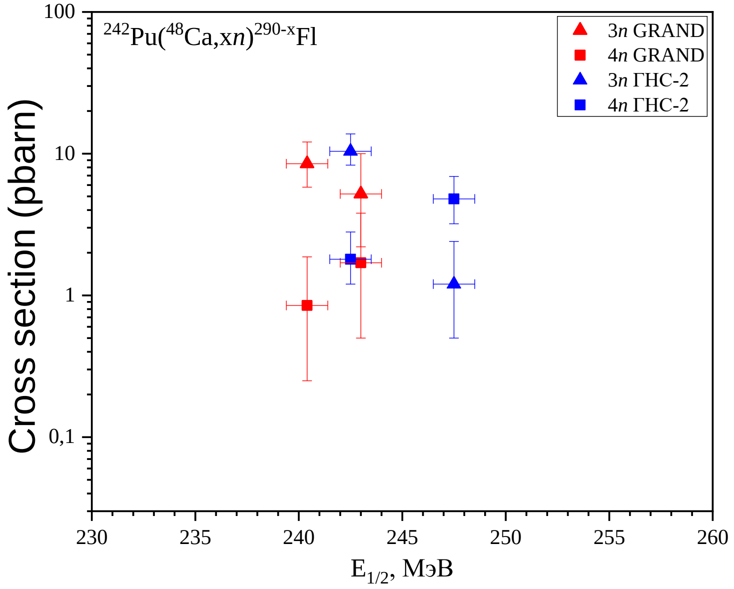
$^{48}Ca + ^{242}Pu \rightarrow ^{290}Fl^*$

E_{lab}, MeV	$E_{1/2}$, MeV	E*, MeV	N(3n)	N(4n)	Integral flux	σ(3n), pbarn	σ(4n), pbarn
252	240.4	38.4	9	2	$4.82 \cdot 10^{18}$	$8.5^{+3.6}_{-2.7}$	$0.85^{+1.0}_{-0.6}$
256	243	40.6	3	2	$2.35 \cdot 10^{18}$	$5.2^{+4.8}_{-3.0}$	$1.7^{+2.1}_{-1.2}$

Target ^{242}Pu – 240 mm, 0.7 mg/cm^2.

Mean beam intensity – 2 pμA.

→ 2 - 3 events / day !

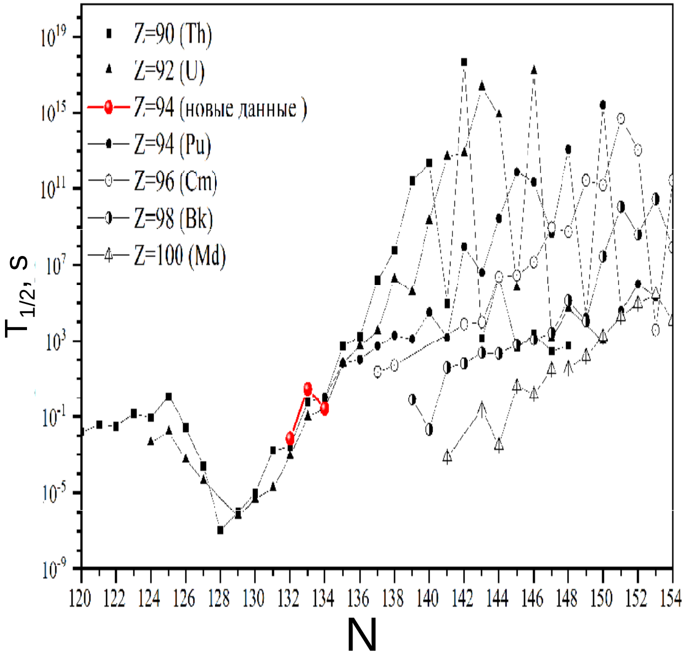


Experimental results obtained to date

June 2023 – GRAND + GABRIELA

Reactions	CN	3n	4n	5n
(1)$^{26}Mg+^{208}Pb$	^{234}Pu	129.8 nb*	21.5 nb*	2.48 nb*
(2)$^{26}Mg+^{206}Pb$	^{232}Pu	0.35 nb	0.15 nb	0.11 nb
(3)$^{26}Mg+^{204}Pb$	^{230}Pu	0.15 nb	0.02 nb	

Isotopes	E_α keV	$T_{1/2}$	E_α keV	$T_{1/2}$	Decay mode
	Experiment			Literature's data	
$^{230}Pu^{gamma}$	6990±16 7057±11	-	6999 7057	102 s	α ~100%
^{229}Pu	7459±10	-	7460	90 s	α ~50% EC~50%
^{228}Pu	7762±37	0.253 s	7810/7772	1.1/0.3 s	α ~100%
				Theory	
$^{227}Pu^{new!}$	8156±26 (b_{EC} = 0,23 ± 0,10)	2.2 s	8153	0,86 s	α ~69% EC ~ 31%
$^{226}Pu^{new!}$	8754±24	≥ 1 ms (1 event!)	8773	1 ms	α ~100%



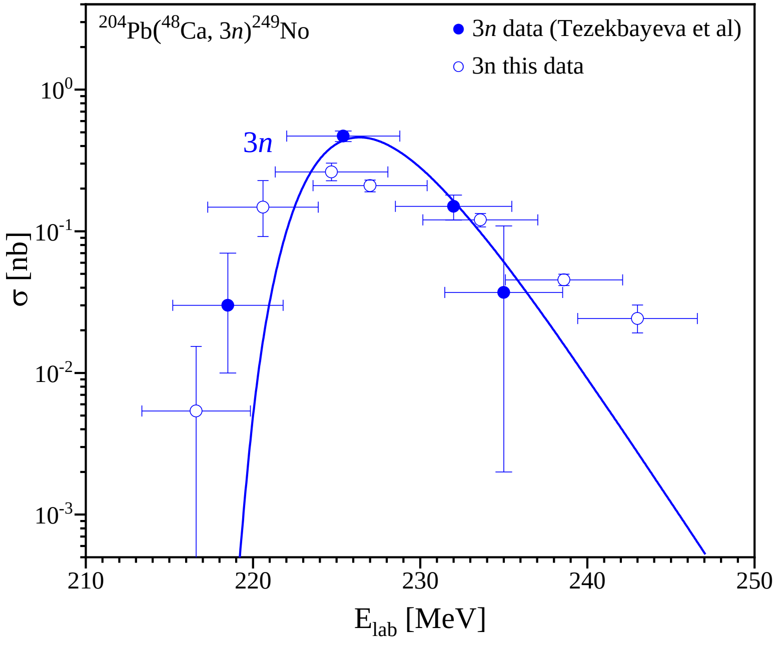
JINR Preprint, P7-2024-50

Experimental results obtained to date

December 2023 – GRAND + GABRIELA

$^{48}Ca + ^{204}Pb = ^{252}No^{*} = 3n + ^{249}No$

Experimental setup	SHELS @U400	GRAND @DC280
Year of experiment	2020	2023
Duration of irradiation	19 days	13 days
Beam intensity	~0.5 pμA	3 pμA
Beam dose	$4 \cdot 10^{18}$	$21 \cdot 10^{18}$
Number of beam energy values	4	7
Number of ^{249}No (ER-α)	200 nuclei	400 nuclei



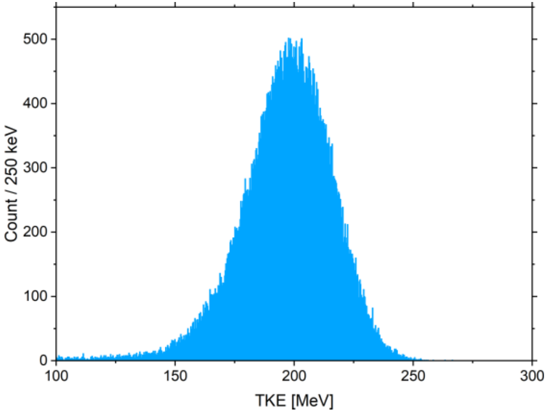
Experimental results obtained to date

April 2024 – GRAND + GABRIELA

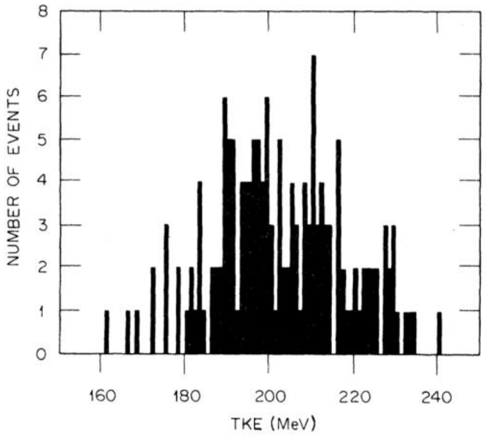
$^{48}Ca + {}^{206}Pb = {}^{254}No^* = 2n + {}^{252}No$

- Target: 690 μg/sm^2 PbS (**480** mm in diam. wheel)
- **Beam: 4-6 pμA of ^{48}Ca**
- **Result: 1-1.5 fissions/s** from SF of ^{252}No implanted to the GRAND focal DSSSD.

GRAND 2024 ~85k SF of ^{252}No

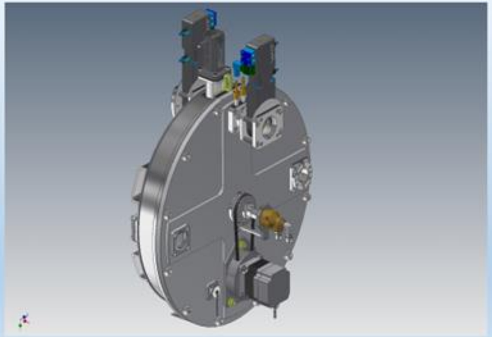


Bemis 1977, 176 SF

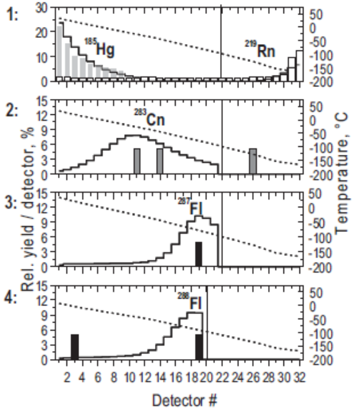


Target wheels with 240 and 480 mm diameter

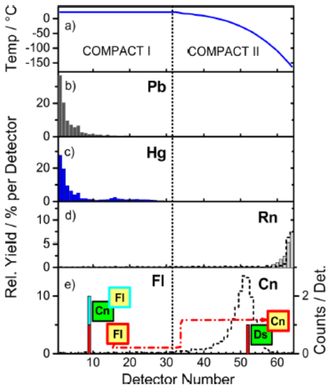
480 mm target wheel assembly design



Chemistry of flerovium and copernicium



R. Eichler *et al.*,
Radiochim. Acta **98**, 133 (2010)



A. Yakushev et al.,
Inorg. Chem. **53**, 1624 (2014)

Is flerovium a metal or a noble-gas-like?

GRAND – pre-separator before a chemical setup

$^{242}Pu + ^{48}Ca$ - for synthesizing Cn and Fl

<u>From the distributions of atoms over the detectors:</u>

1. adsorption properties of Cn and Fl

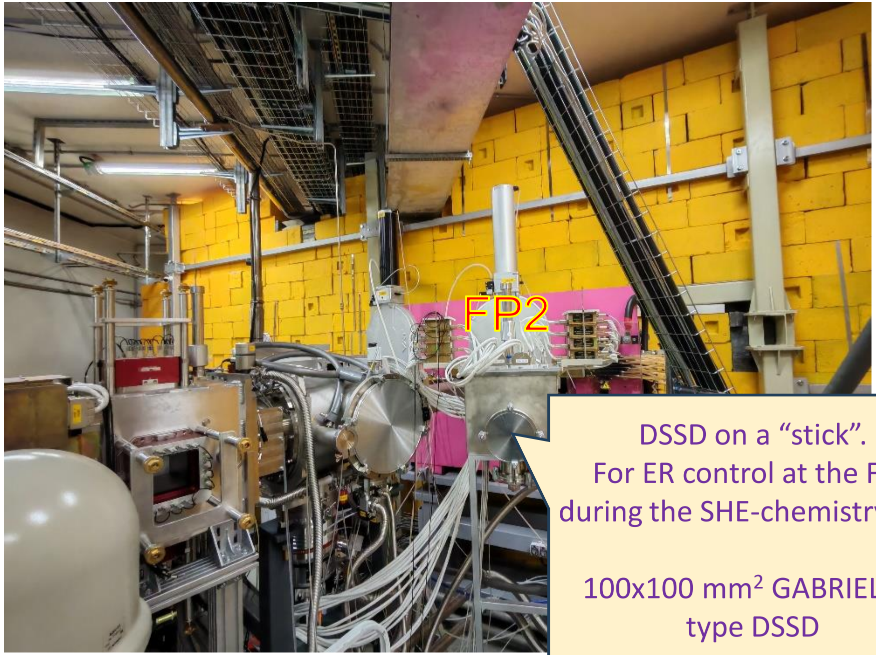
2. thermodynamic characteristics of Cn and Fl compared with their light homologues Hg and Pb

3. experimental determination of the influence of relativistic effects on the chemical properties of the heaviest elements.

4. degree of compliance of the chemical behavior of the SHE with the law of periodicity of properties

Chemistry of flerovium and copernicium

Optimization of Cryodetector setup for ^{287}Fl experiments behind the GRAND



DSSD on a "stick".
For ER control at the FP2 during the SHE-chemistry run.

100x100 mm^2 GABRIELLA-type DSSD

New RTC:

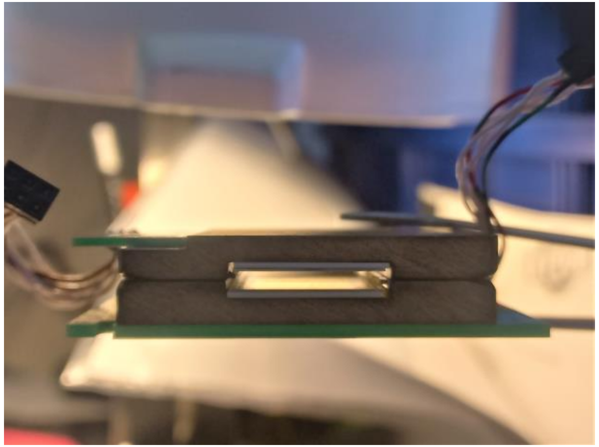
- FP effective area vs $T_{1/2}$ Fl-287
- Stopping range measurments
  - Mylar thickness
  - He/Ar mixture
- Gas flows modeling

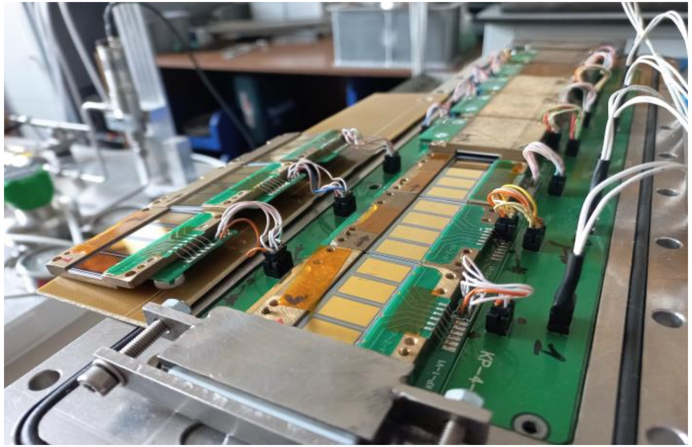
- New cooling + stability test (temp. gradient)
- New detection modules with gold surface
- Gas composition control and leaking tests

- Tests with short-lived isotopes Hg
- Etc.

Chemistry of flerovium and copernicium

New detection modules with gold surface

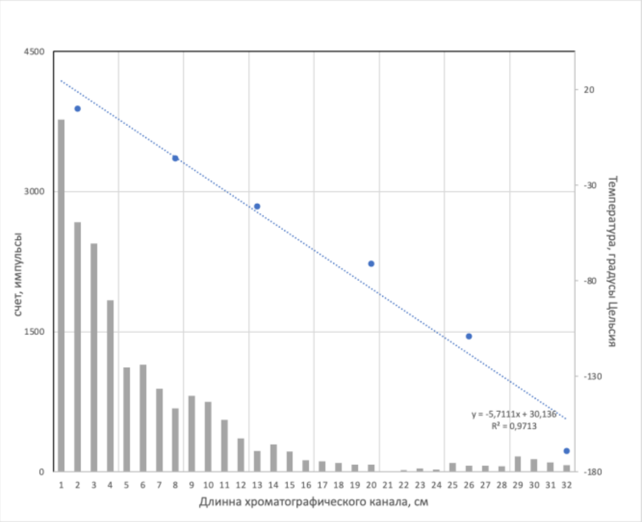




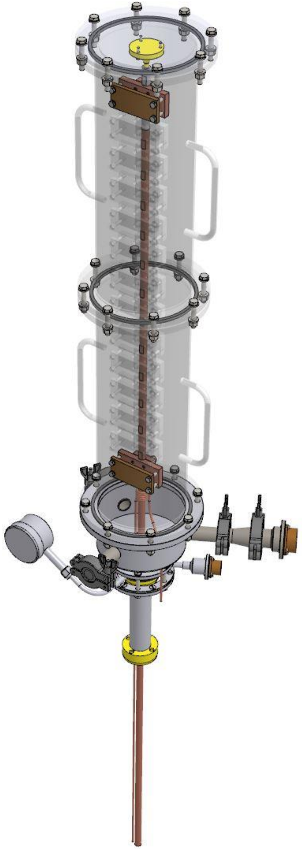
Chemistry of flerovium and copernicium

R/D of CRIO-bench for Si-dets colling and LN consumption optimization

New LN cooling system



Cryodetector



Chemistry of flerovium and copernicium

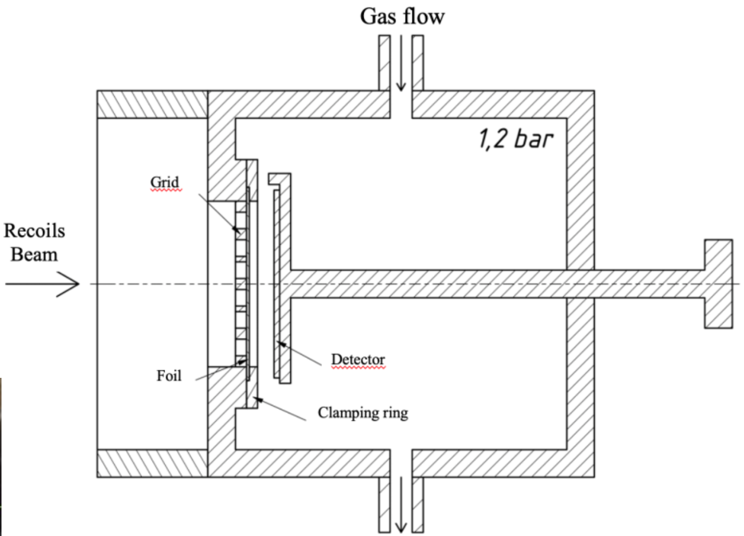
New RTC for He/Ar gas: Stopping range measurements

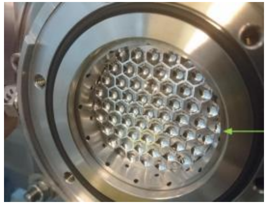
$^{208}Pb(^{48}Ca, 2n)^{254}No$

$^{144}Sm(^{40}Ar, xn)^{184\text{-}n}Hg$

$E_R = 39.6$ MeV

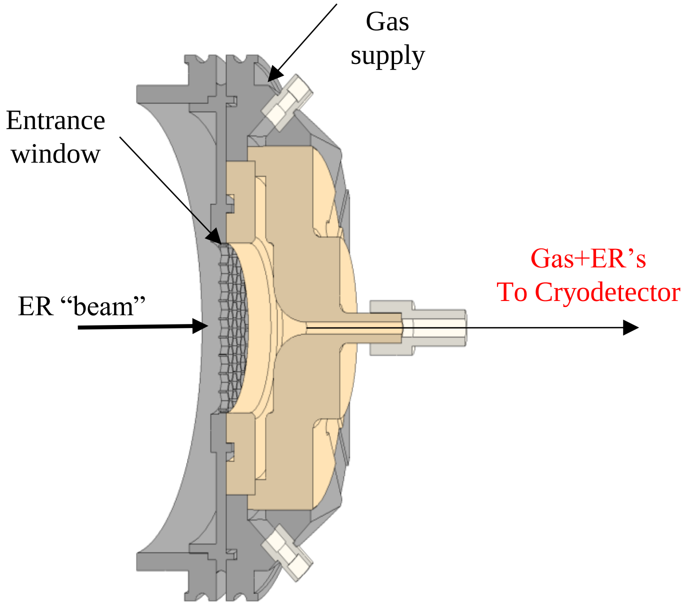
$E_R = 47$ MeV

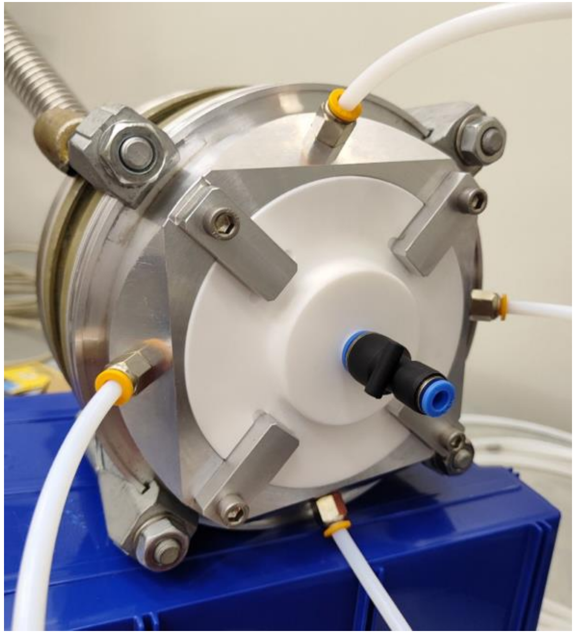




Chemistry of flerovium and copernicium

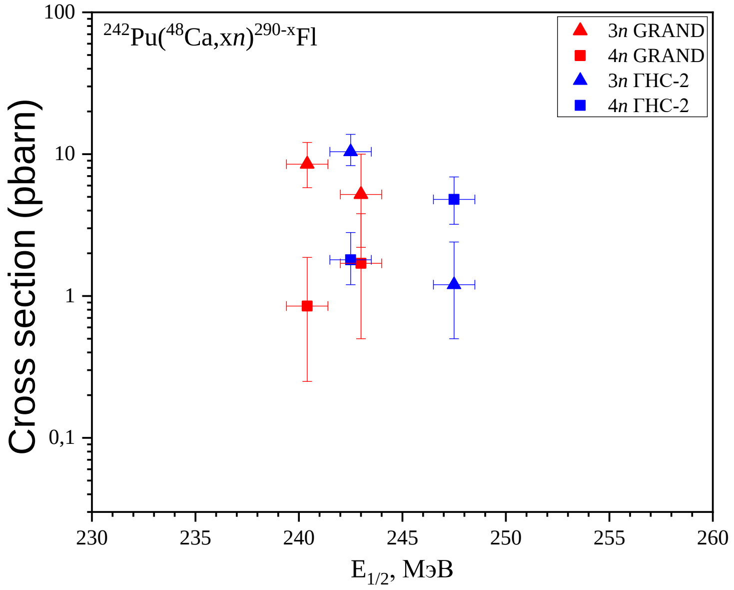
New RTC





total gas renewal time = 1.6 s, Hg transport time = 0,2 s!

Chemistry of flerovium and copernicium



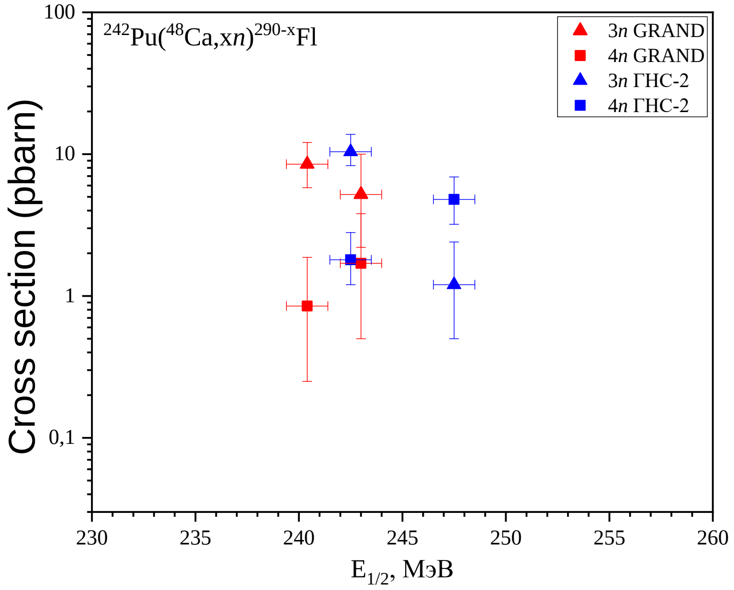
Cross section ≈ 10 pb (3n)

σ = 10 pb, h_t=0.7 mg/cm^2, $Ø_t$ = 480 mm,

ε_{GRAND}=0.6, I_{beam}=4-6 pmA → ≈ **12-16 Fl(Cn)/day** × ε_{CRYO}

$\varepsilon_{CRYO} = \varepsilon_{RTC} \times \varepsilon_{Ads.} \times \varepsilon_{transp.} \cdots$

Chemistry of flerovium and copernicium



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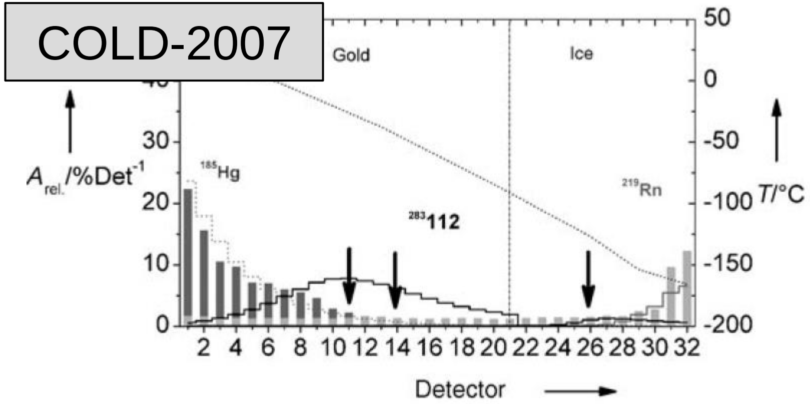


R. Eichler et.al, *Angew. Chem. Int. Ed. 2008, 47, 3262*

3 events of ^{283}Cn per 3.1x10^{18} ^{48}Ca ions from U400 cyclotron **(16 days!)**

? events of ^{283}Cn per 2.5x10^{18} ^{48}Ca ions from DC280 cyclotron **(1 day!)**

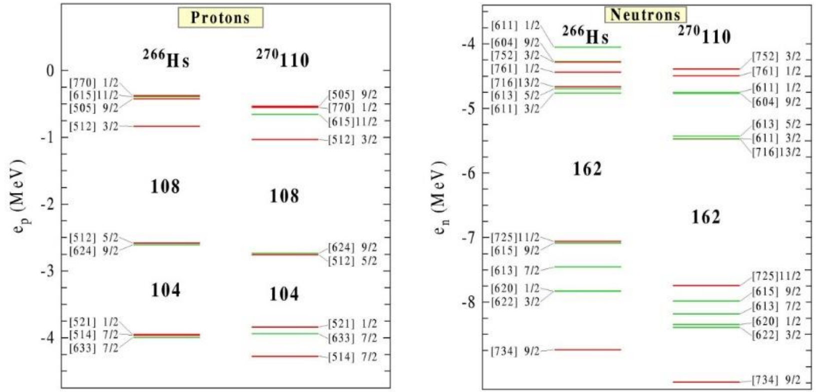
Spectroscopy of SHE at GRAND

- <u>**Location of closed shells:**</u>
- Proton shell:
- 114, 120 or 126 / 114 – 126 ?
- Neutron shell:
- 172 or 184 ?

- <u>**Nuclear structure:**</u>
- Lifetimes
- Decay modes
- Isomers

<u>**Single particle energies:**</u>

Energy gaps at Z = 108 and N=162



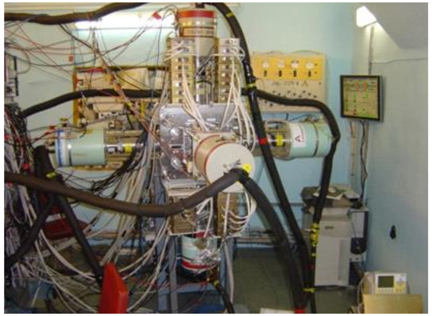
Experimental insight into the sructure of Super Heavy Nuclei can be obtained by direct measurements of the ground states properties of nuclei. The production cross sections beyond element 110 are very low => 1 pb, this fact increase the importance of the investigations in the region Fm - Sg

Spectroscopy of SHE at GRAND

Main goal of our activity in Spectroscopy of heavy nuclei :

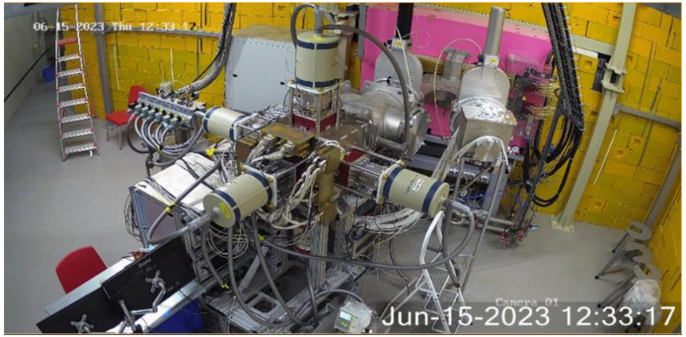
1. Spectroscopy experiments using high resolution alpha, CE spectroscopy and Ge arrays to study Decays of No, Lr, Rf, Db and Sg isotopes and daughter nuclei.

GABRIELA-II, 1 Clover, 4 single crystal HPGe detectors.
SHELS @ U400
GABRIELA-III, 5 Clover HPGe detectors,
thick tunnel detectors for detecting CE.
GRAND @ DC280.

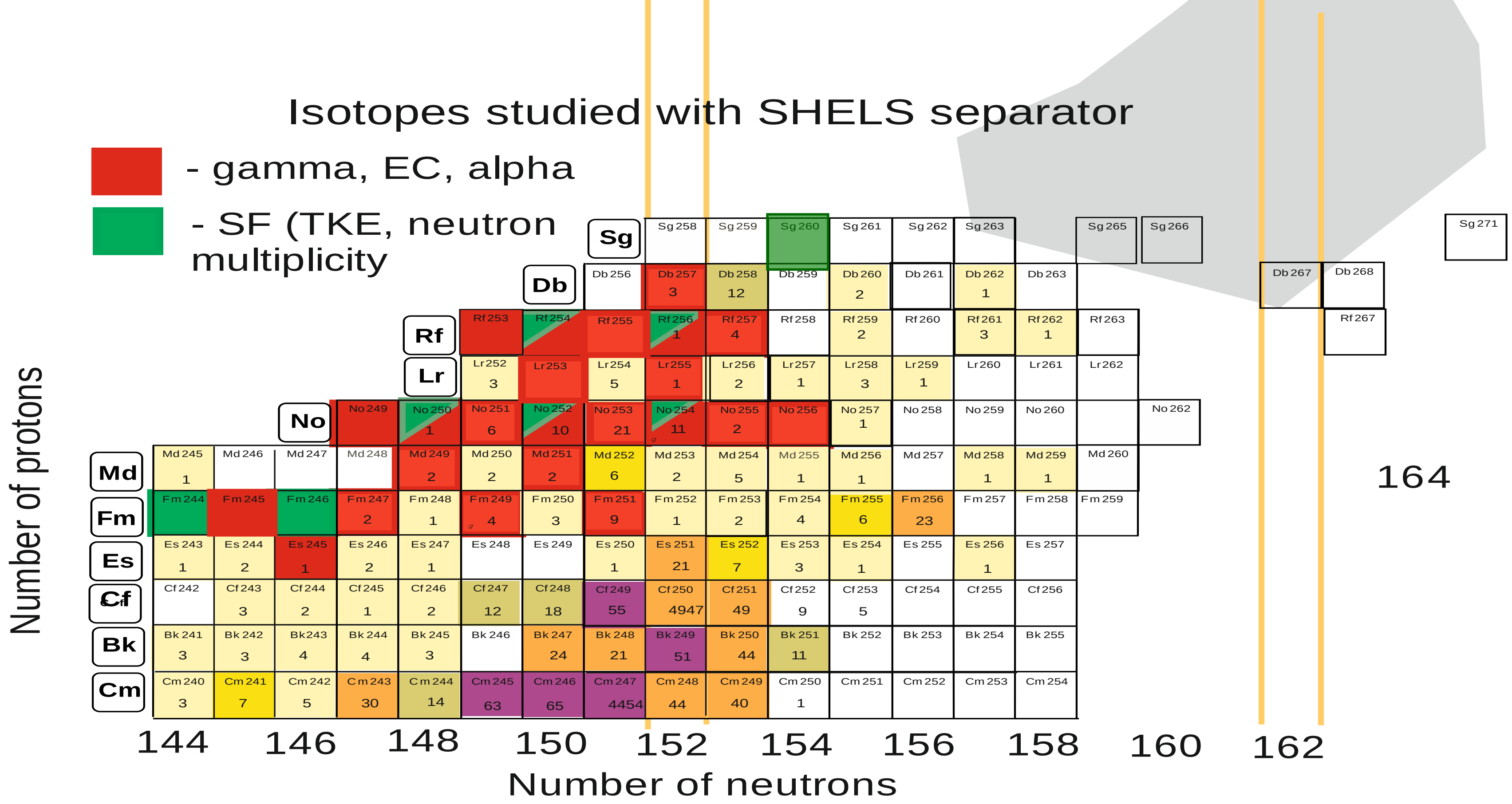


2. Full scale experiments aimed to spectroscopy studies of ^{286,287}Fl, ^{288}Mc and daughter nuclei.

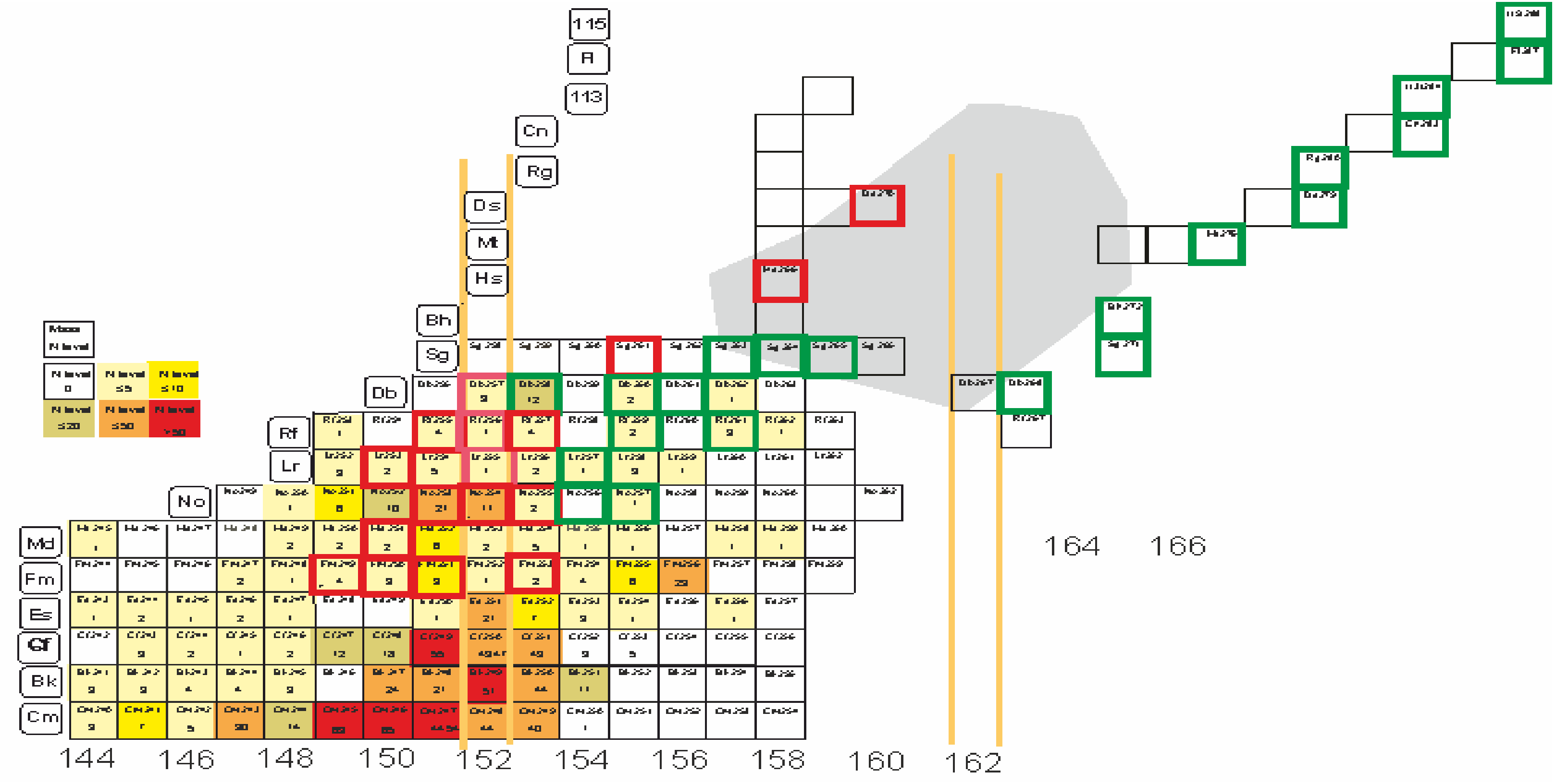
GABRIELA-III, 5 Clover HPGe detectors,
thick tunnel detectors for detecting CE.
GRAND @ DC280.



Spectroscopy of SHE at GRAND



Spectroscopy of SHE at GRAND



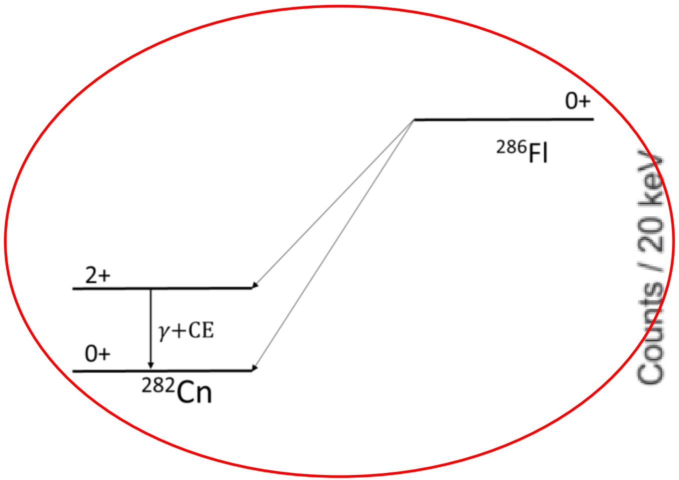
Spectroscopy of SHE at GRAND

april 2024

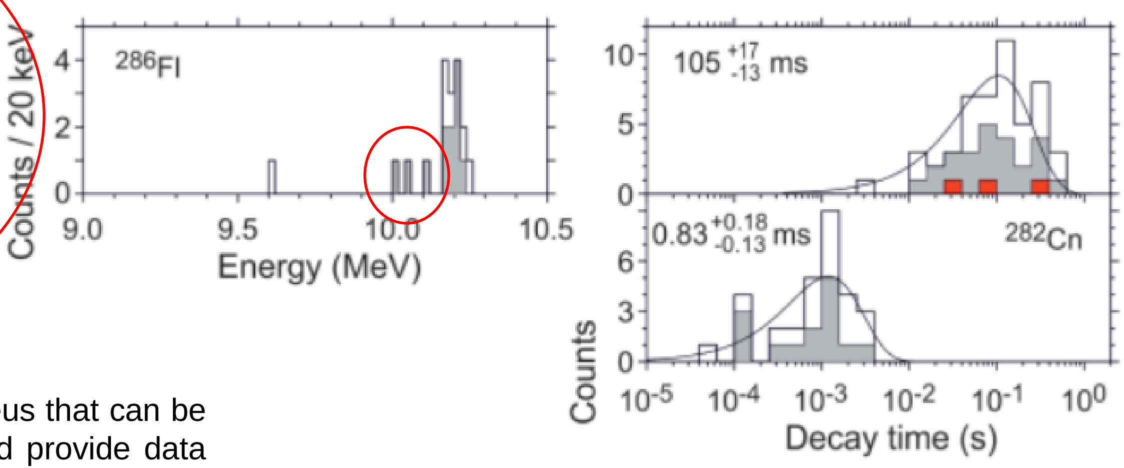
GRAND + GABRIELA – III

- **$^{48}Ca + ^{206}Pb = 2n + ^{252}No$**
- Target: 690 μg/sm^2 PbS (**480** mm in diam. wheel)
- **Beam: 4-6 pμA of ^{48}Ca**
- **Transmission – 40%**
- **Result: 1-1.5 fissions/s** from SF of ^{252}No implanted to the GRAND focal DSSSD.

Spectroscopy of SHE at GRAND



^{242}Pu+^{48}Ca reaction products (DGFRS2)



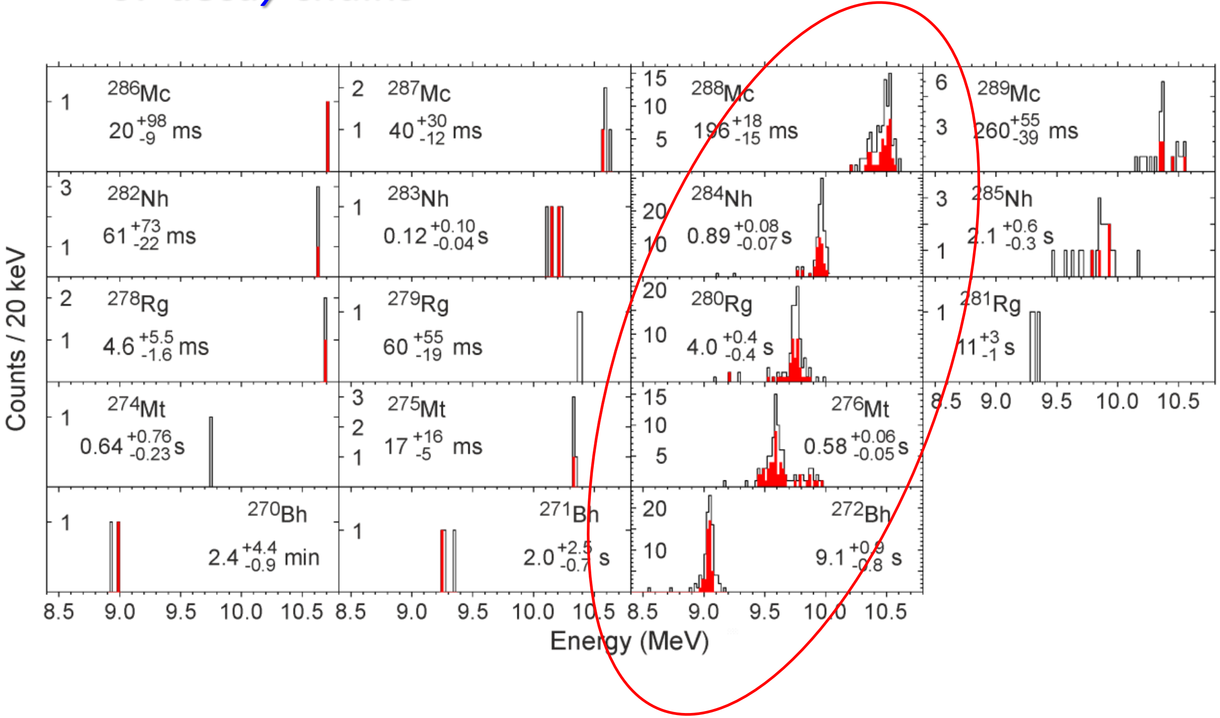
The several hundred α-decays of this nucleus that can be recorded during a 60-day experiment could provide data on the lowest levels (0+, 2+) of the ground state transition of the nucleus ^{282}Ds. These data directly indicate the degree of deformation of the studied nucleus, i.e., the distance of the nucleus from the hypothetical region of spherical superheavy nuclei ("Island of Stability").

Yu. Ts. Oganessian et. al,
PHYSICAL REVIEW C **106**, 024612 (2022)

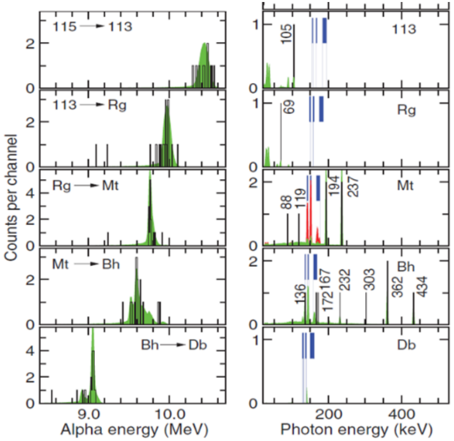
Spectroscopy of SHE at GRAND

Reaction $^{243}Am(^{48}Ca,2\text{-}5n)^{286\text{-}289}Mc$ (DGFRS2)

67 decay chains

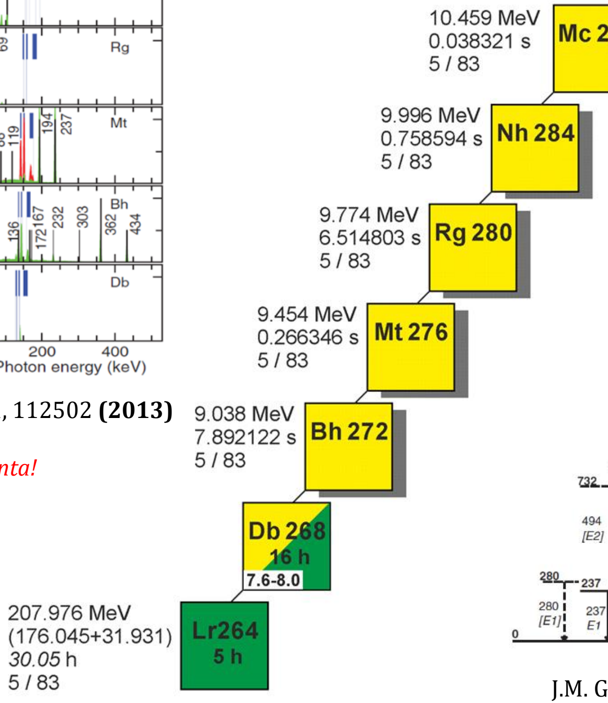


Spectroscopy of SHE at GRAND



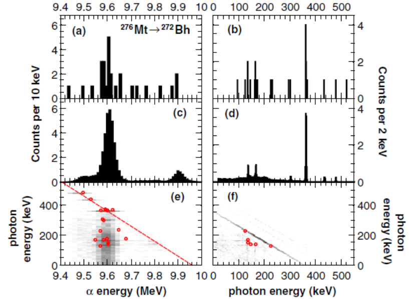
D. Rudolph *et. al.*, PRL 111, 112502 **(2013)**
TASCA + TASISpec
22 decay chains - 16 γ-quanta!

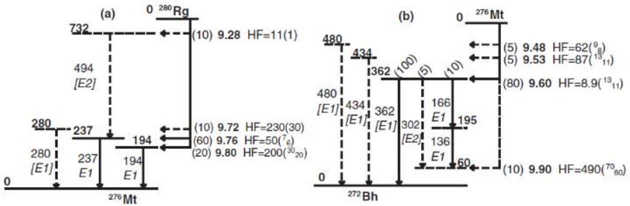
$^{243}Am + ^{48}Ca$



55 new decay chains
(+31 in 2003, 2010-2012)

SHE Factory, DGFRS II **(2021)**





J.M. Gates *et. al.*, Phys. Rev. C. 92, 021301(R) **(2015)**
BGS + C3

Spectroscopy of SHE at GRAND

$^{48}Ca + ^{242}Pu \rightarrow ^{286}Fl + 4n$

target D = 480 mm

cross section ^{286}Fl ~ 5 pbarn

^{48}Ca ~ 3×10^{13} pps. (5-6 pμA)

$\varepsilon_{transmission}$ ~ 40 %

$\rightarrow$ **5 - 7 ^{286}Fl** / day

100 days $\rightarrow$ 10^{20} ^{48}Ca ions $\rightarrow$ **500 - 700 ^{286}Fl**

Spectroscopy of SHE at GRAND

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

target D = 480 mm

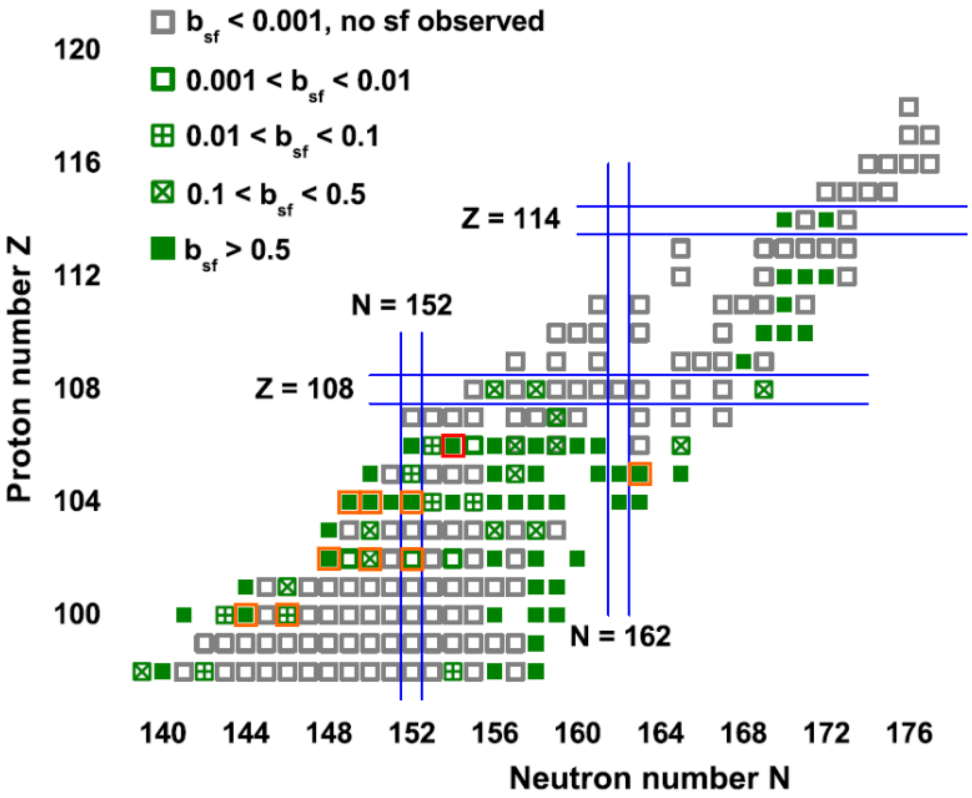
cross section ^{288}Mc ~ 8 pbarn
^{48}Ca ~ $3x10^{13}$ pps. (5-6 pμA)
$\varepsilon_{transmission}$ ~ 40 %

$\rightarrow$ **6 - 8 ^{288}Mc** / day

100 days $\rightarrow$ 10^{20} ^{48}Ca ions $\rightarrow$ **600 - 800 ^{288}Mc**

The work can only be carried out once the "SHE Factory" has been upgraded to a Class-I RC-laboratory.

Spontaneous fission properties of SHE

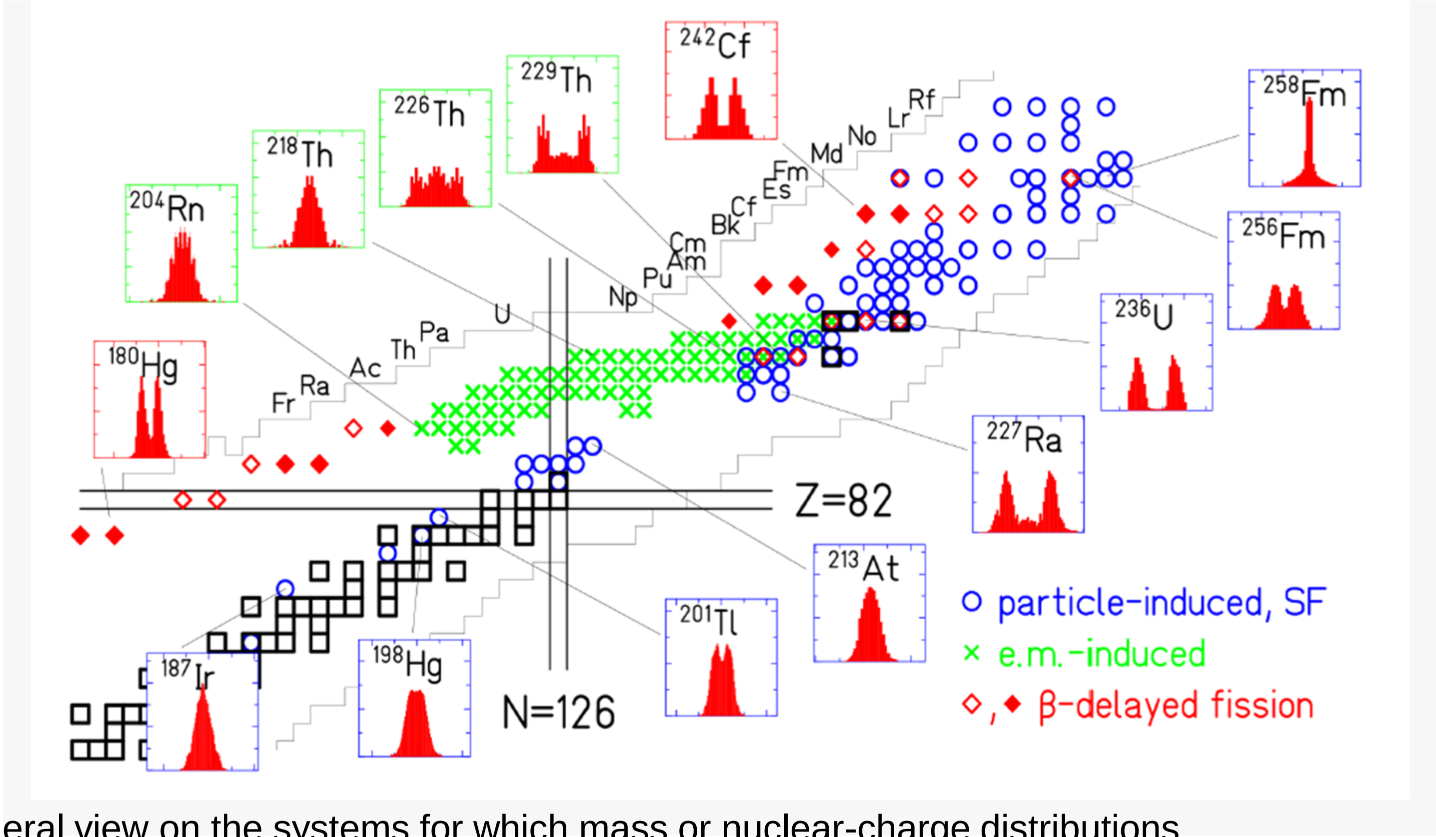


the isotopes for which spontaneous fission branches have been reported so far.

*F.P. Hesberger - Eur. Phys. J. A (2017)**53, 75***

The orange and red boxes – SF nuclei which have been studied on the VASSILISA (SHELS) separator

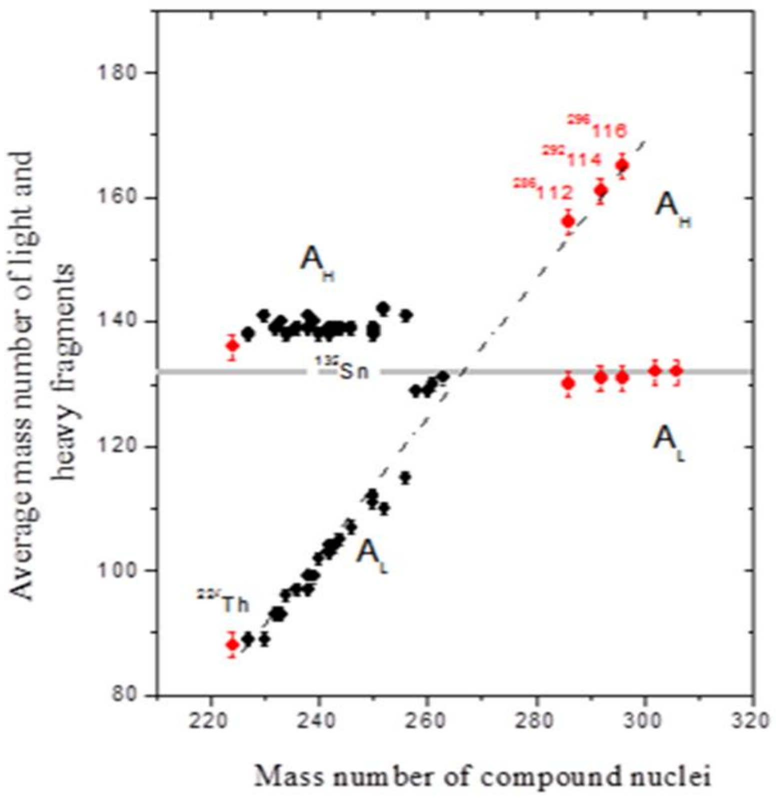
Spontaneous fission properties of SHE

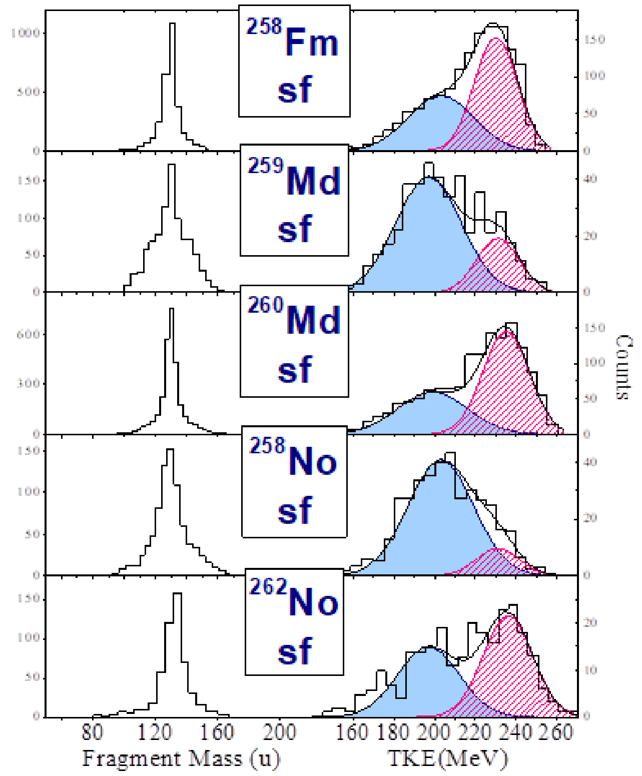


General view on the systems for which mass or nuclear-charge distributions have been measured.

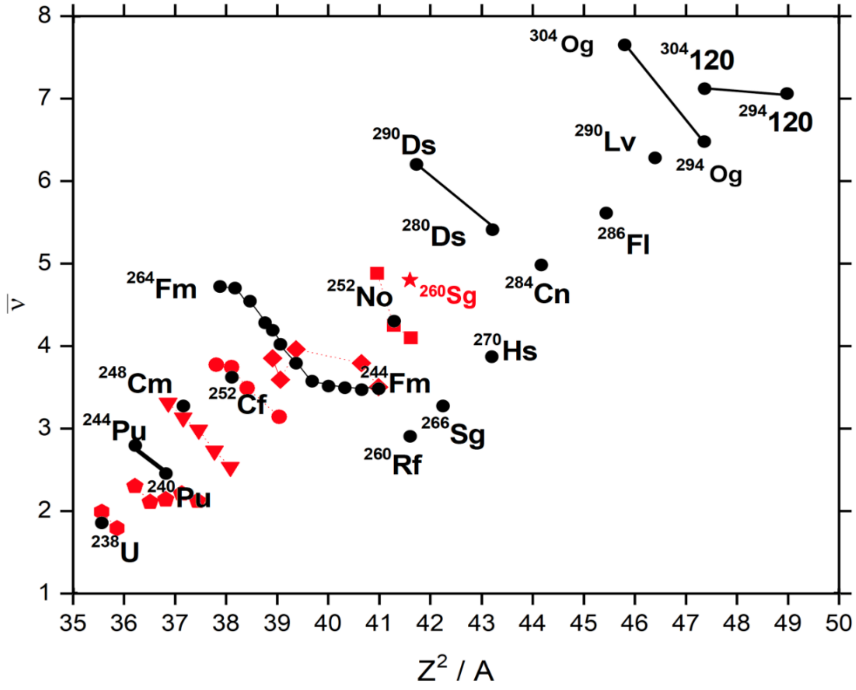
K.H. Schmidt, B. Jurado, Rev. Prog. Nucl. Fiss (2018)

Spontaneous fission properties of SHE



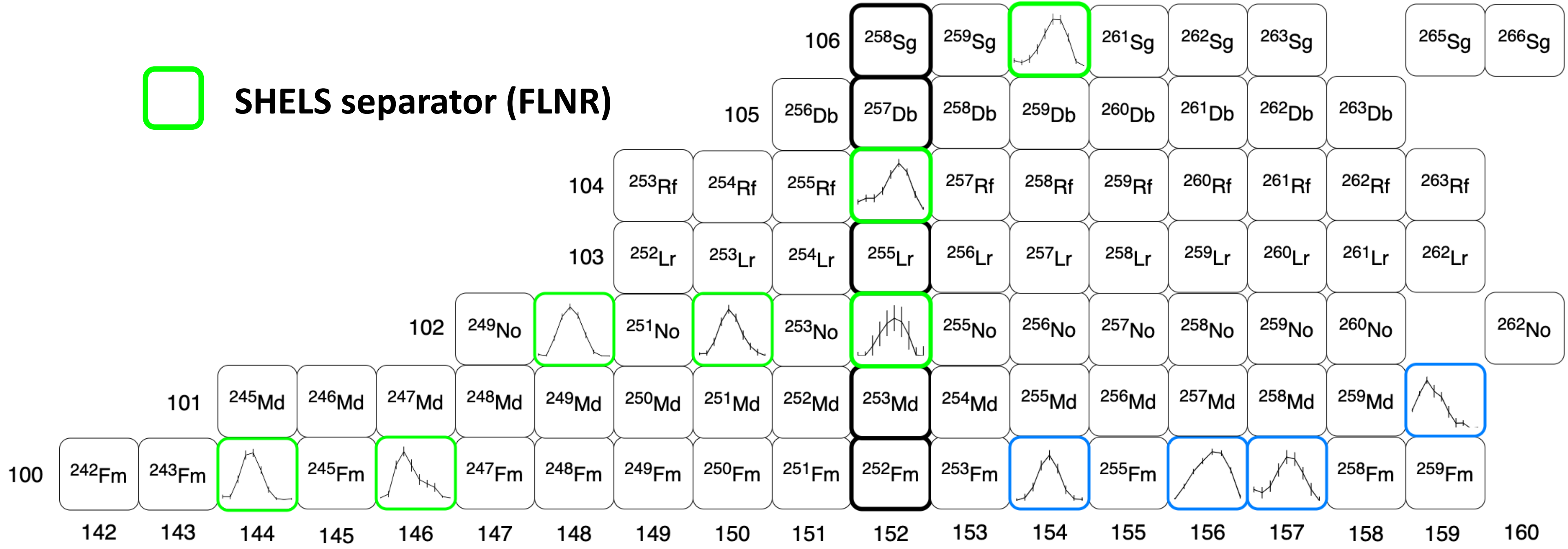


Spontaneous fission properties of SHE



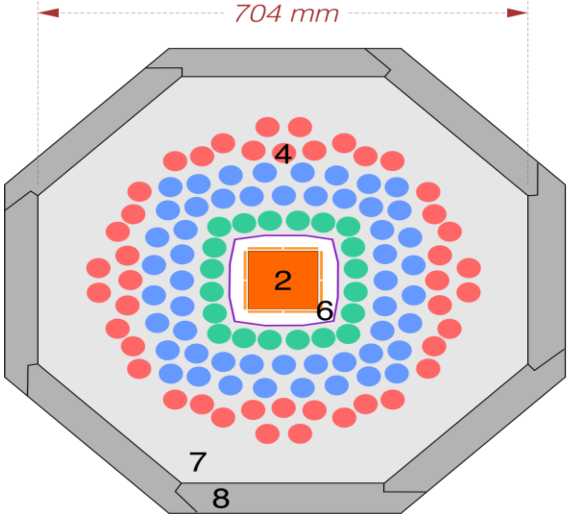
Rubchenya, V.A. Prompt neutron characteristics
in the spontaneous fission of heavy and superheavy nuclei.
LXV International Conference "Nucleus 2015" June 29-July 3, 2015, St. Petersburg

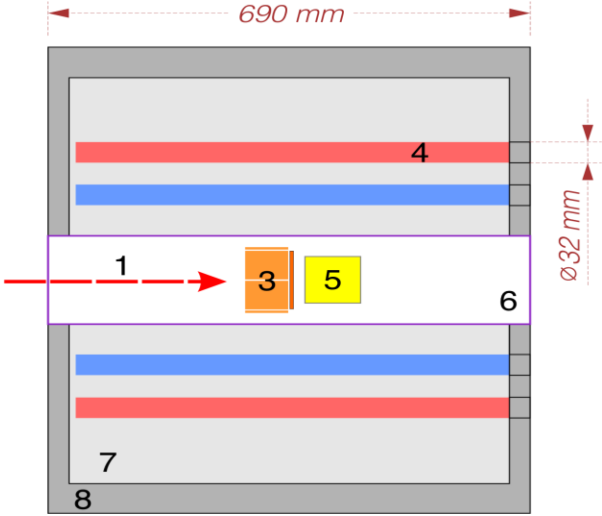
Spontaneous fission properties of SHE



Spontaneous fission properties of SHE

SFiNx
Spontaneous Fission, Neutrons and x-rays



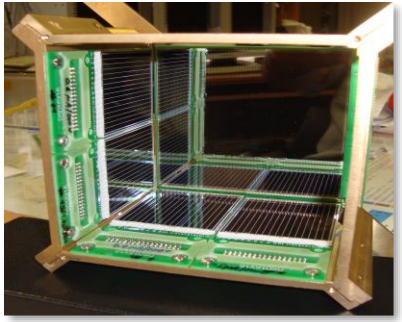


Isaev, A. V. et al.
The SFiNx detector system
PEPAN Letters 19, 37–45 (2022)

Isaev, A. V. et al.
Study of spontaneous fission using the SFiNx system
APP B Proc. Suppl. 14, 835–839 (2021)

1 – ER “beam”
2,3 – DSSSD box
4 - ^{3}He-based N counters
5 – scintilator
6 – vacuum chamber
7 – neutron moderator
8 – neuron shield

$\varepsilon_n = 55\%$



DSSD 100×100 мм
128×128 strips

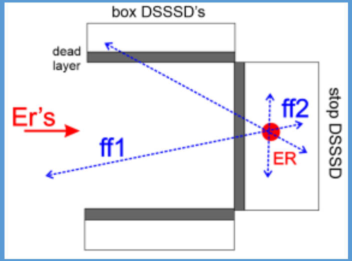
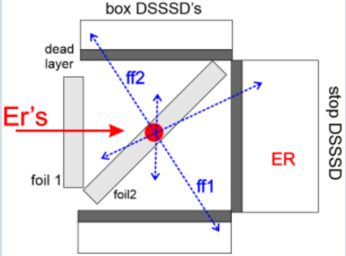
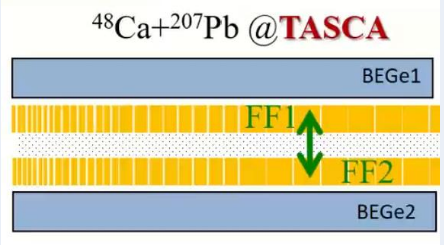
Spontaneous fission properties of SHE

The estimation of half life	>	5 decays
The average number of SF neutrons (ε_n > 45%)	>	20 fissions
The determination of neutron multiplicity distribution (ε_n > 45%)	>	100 fissions
The evaluation of TKE (2 FF!)	>	100 fissions
The determination of energy or mass distribution of single fission fragments	>	**10^5 fissions**

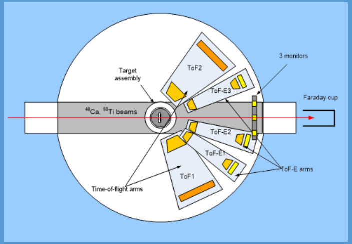
Spontaneous fission properties of SHE

To create the correct mass distribution of fission fragments we need to register **≥ 10^5 fission fragments !!!**

	^{254}No	^{252}No (April 2024)
Cross section of ER formation	2000 nb	186 nb
Branching ratio	b_α= 90% (b_{sf} = 0.17%)	b_{SF} = 33%
Efficiency of detection	ε_α = 50%	ε_{SF} = 100%
I beam = **1 pμA of ^{48}Ca**	120 000 **alphas** from ^{254}No per 24h	25 000 fissions of ^{252}No per 24h
I beam = 6 **pμA of ^{48}Ca**	720 000 **alphas** from ^{254}No per 24h *2500 fissions from ^{254}No per 24h*	**100 000 fissions of ^{252}No per 24h**

The implantation "box" detector 	**ε_{det} = 100 %** **100 000 F1 or F2 events per 24h** **F1 and F2 ε_{det} = 50 %** **50 000 F1+F2 events per 24h**	**2E method (+ neutrons)** **TKE + neutrons!** **Mass measurements not supported**
The "box" + inclined film 	ε_{det} = 3-5 % 1 500 - 2 500 SF events per 24h	2E method (+ neutrons) TKE, fr. masses, neutrons 5 < ΔM < 10 amu
ANSWERS-like setup 	<u>ε_{det} = 80-90 %</u> ε_{tr} ≈ 50% (for nobelium!) **40 000 – 50 000 SF** events per 24h	2E methods TKE, fr. masses, neutrons 5 < ΔM < 10 amu

Recoil separator + CORSET-like detector

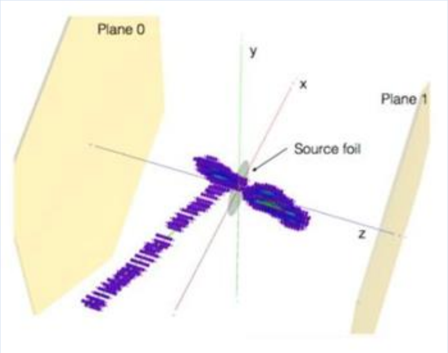


ε_{det} = 0.2 %

200 SF events per 24h

2V, TOF-E methods
TKE, fr. masses
2 < ΔM < 4 amu

Recoil separator + TPC



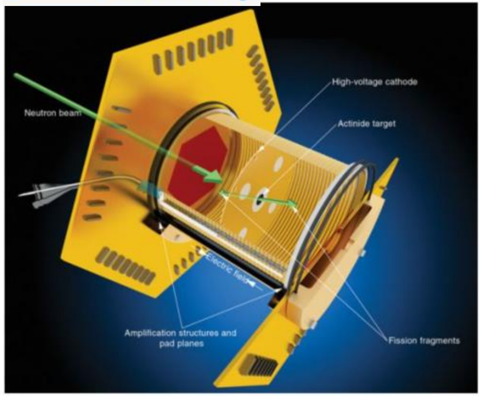
F1+F2 ε_{det} ~ 90 %
90 000 SF events
per 24h

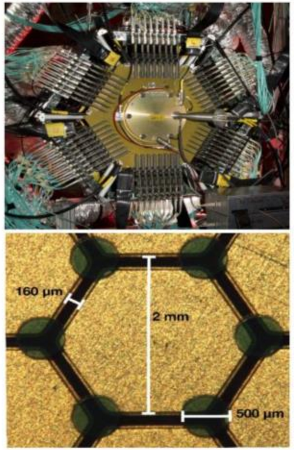
2E + Bragg curves (Z !?)
+ prompt neutrons?
TKE, fr. masses, neutrons
ΔM ~ 7 amu

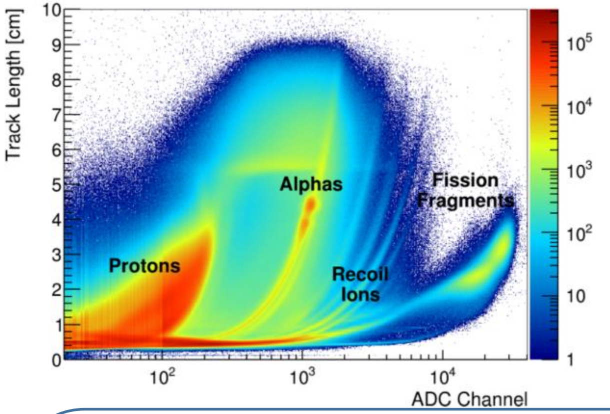
bonus: triple fission observation!

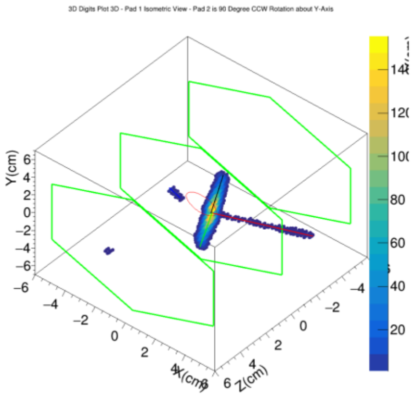
Spontaneous fission properties of SHE

Time projection chamber (TPC)



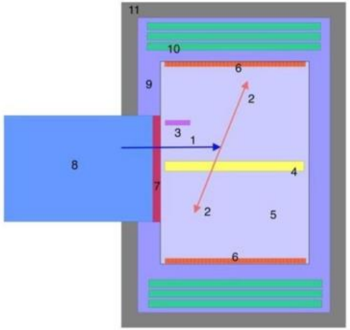


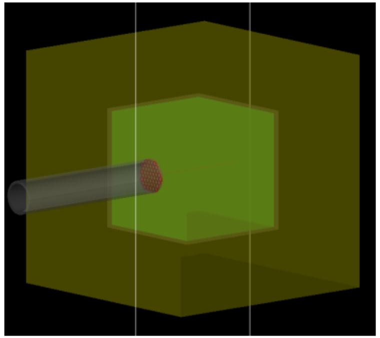




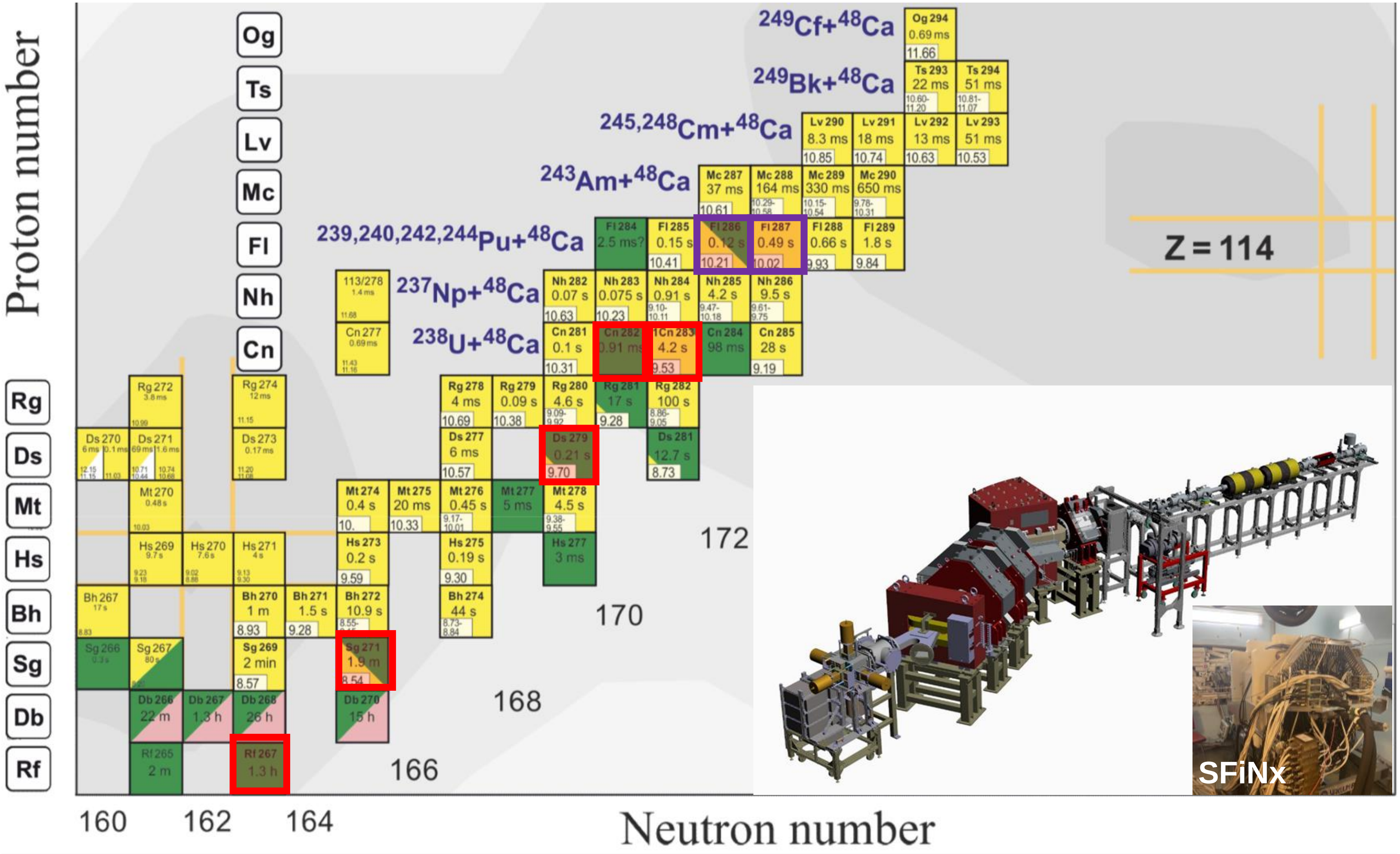
Ruz J. et al.
The NIFFTE project.
Journal of Instrumentation 8/12 (2013)

TPC-concept for SF study of SHE





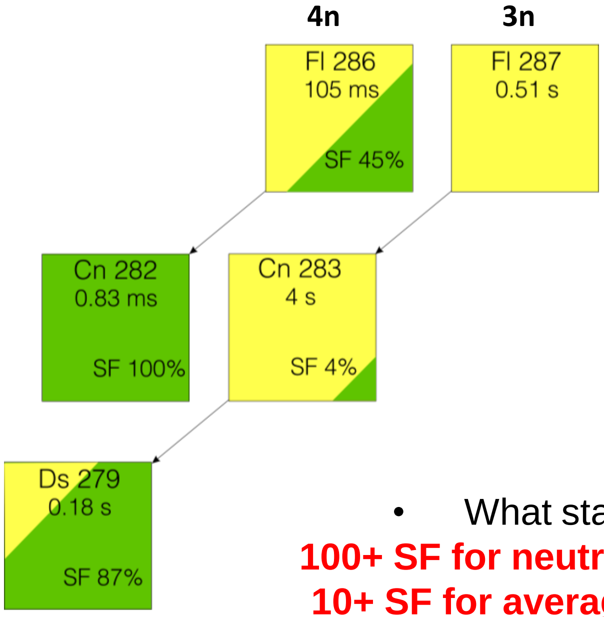
Spontaneous fission properties of SHE

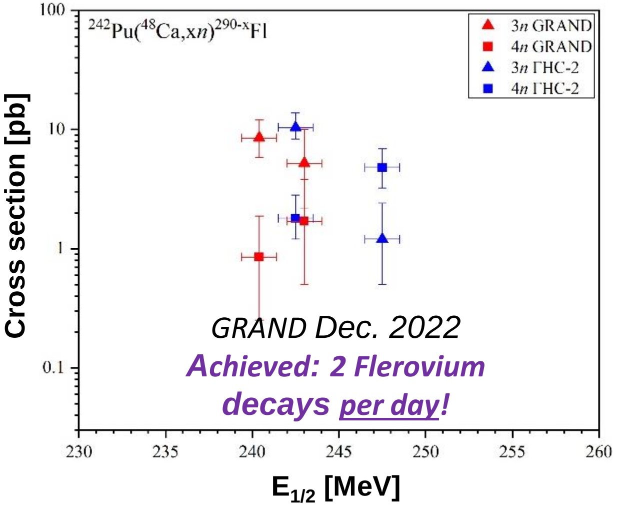


Spontaneous fission properties of SHE

First tests of new rotating target
D = 480 mm and **6 pμA** *of ^{48}Ca*
SHE Factory, April 2024

$^{48}Ca + ^{242}Pu$

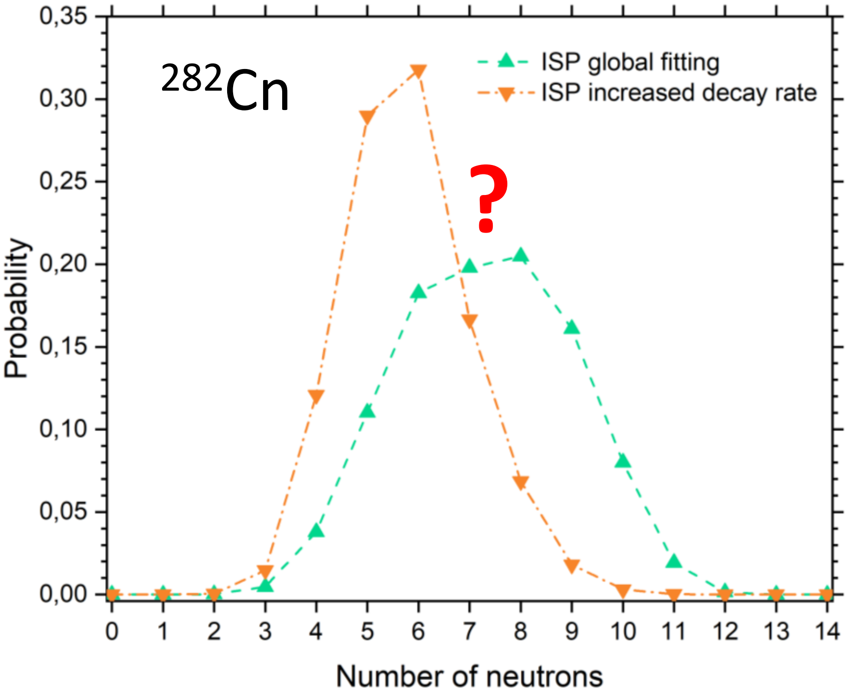




- What statistics are needed?

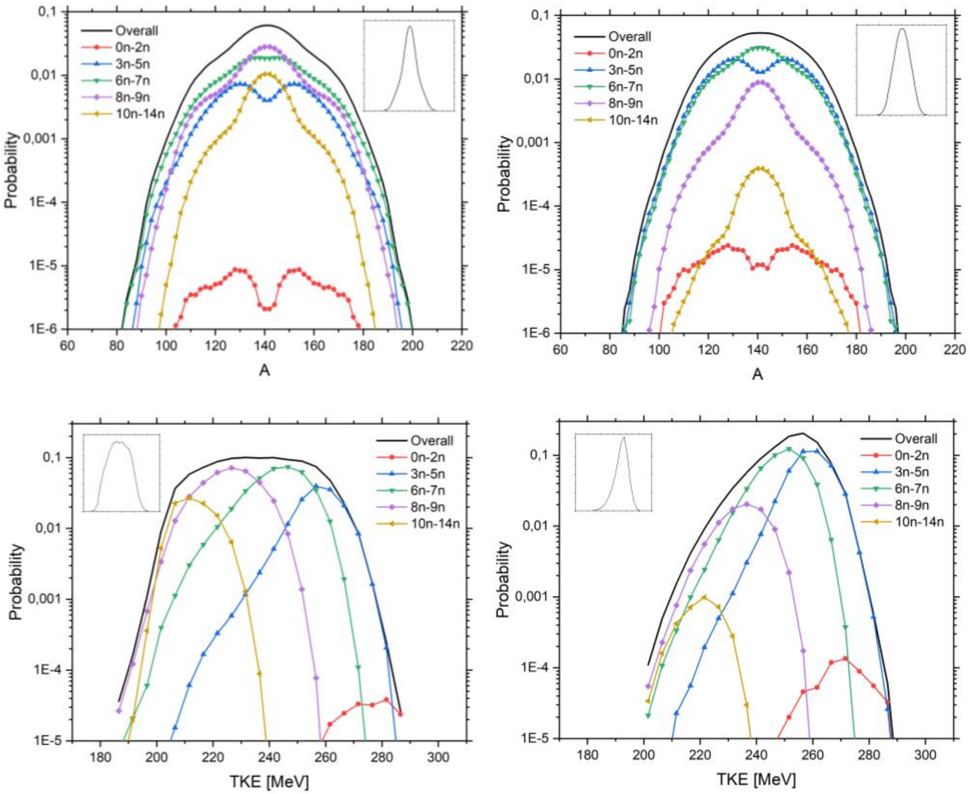
100+ SF for neutron multiplicity and TKE
10+ SF for average number of neutrons
4-5 SHE-isotopes in the **one experiment!!!**

Spontaneous fission properties of SHE



ISP global fitting

ISP increased decay rate



Calculations with additional version of ISP model made by BLTP JINR:

A. V. Andreev, T. M. Shneidman and A. Rahmatinejad

Reaction	Nuclei	Number of nuclei in the focal plane of the separator	Properties of nuclei available for study
$^{48}Ca + ^{204-208}Pb$	$^{249-254}No$	≤ 2.5x10^5 / 24h	α-,β-,γ-spectroscopy, fission fragment spectroscopy (TKE, ff-masses, neutron multiplicity)
$^{48}Ca + ^{242}Pu$	$^{286,287}Fl$ $^{282,283}Cn$…	≤ 10 / 24h	Transactinide chemistry, decay modes, α-,β-,γ-spectroscopy, spontaneous fission characteristics (TKE, neutron multiplicity)
$^{48}Ca+^{243}Am$	^{288}Mc Nh,Rg,Mt…	≤ 10 / 24h (RCL – I)	Transactinide chemistry, decay modes, α-,β-,γ-spectroscopy, spontaneous fission characteristics (TKE, neutron multiplicity)

Thank you for your attention!