Flerov Laboratory of Nuclear Reactions, JINR

Experiments on the physical and chemical properties of SHE at FLNR: status and plans

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Introduction

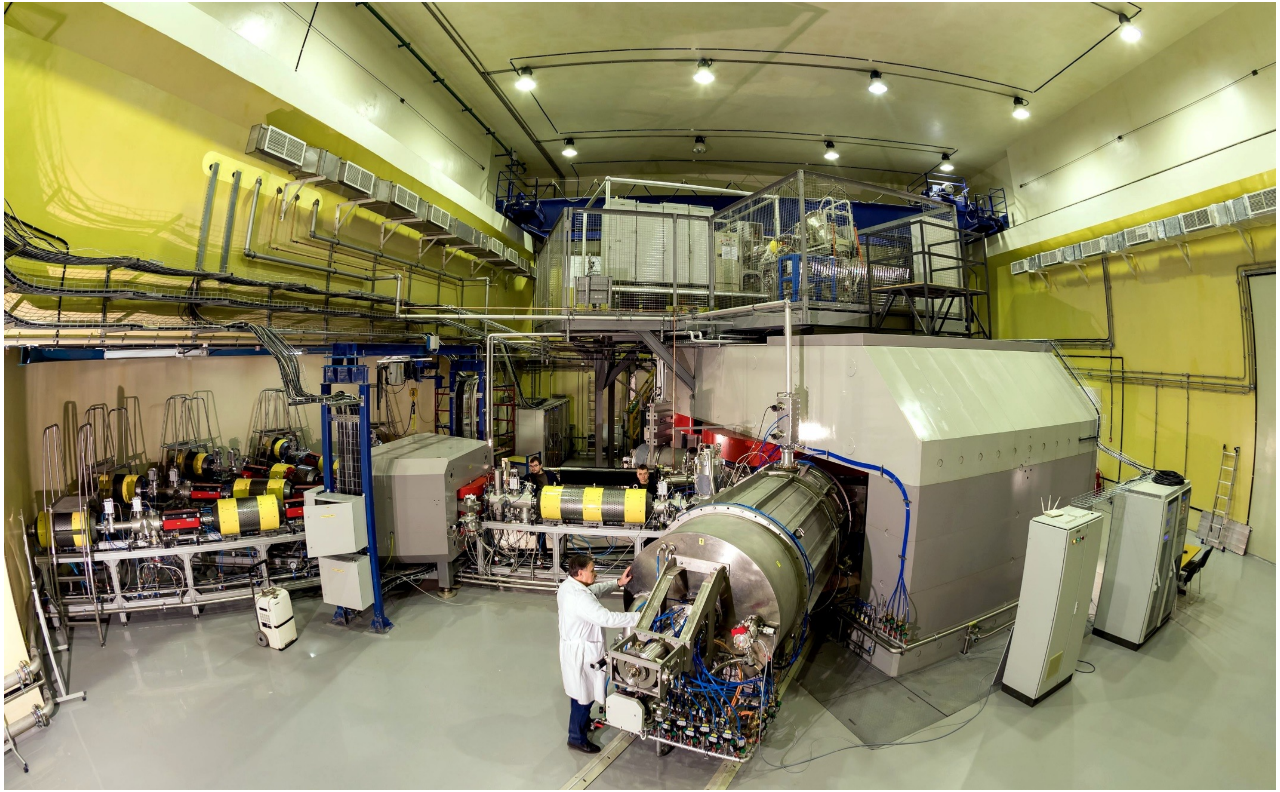
Factory Activities:

- The Heart of SHE Factory – DC-280 Cyclotron
- The synthesis of heaviest nuclei with DGFRS-2
- Spectroscopy of SHE with GABRIELA
- The 480 mm diameter target on GRAND
- Neutron and Gamma Backgrounds
- Spontaneous Fission of SHE with SFiNx
- SHE Mass Measurements
- Chemistry of SHE on GRAND
- Chemistry of SHE with GASSOL

The Heart of SHE Factory – DC-280 Cyclotron

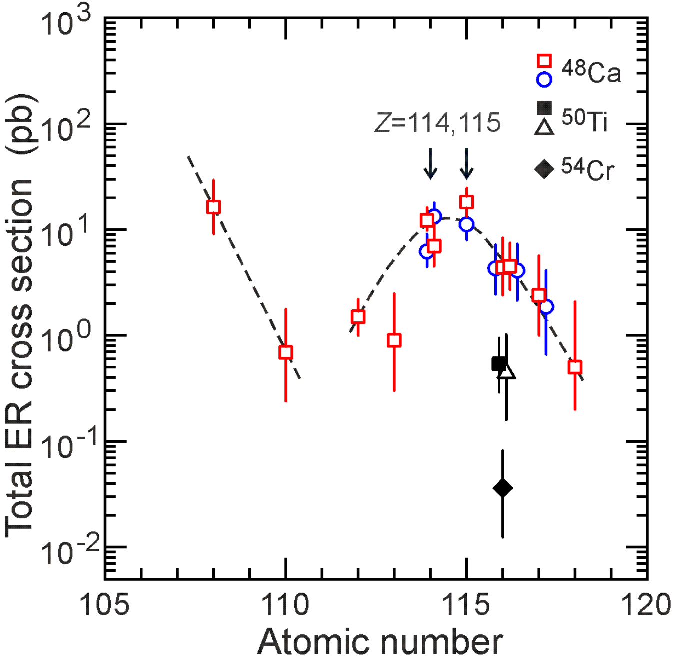
Current status:

- > **8 pμA** of ^{48}Ca of extracted beam have been achieved
- Long-term stable **5 pμA** of ^{48}Ca on GRAND separator target with **stable** energy



The synthesis of heaviest nuclei with DGFRS-2

FLNR Sector #1: V.K. Utenkov, et al.



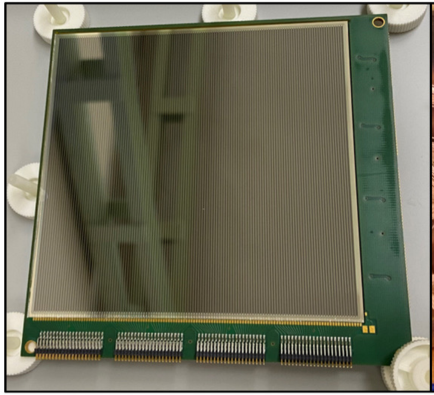
Current status:

- **Preparation for synthesis of 119 and 120 elements**

Spectroscopy of SHE with GABRIELA

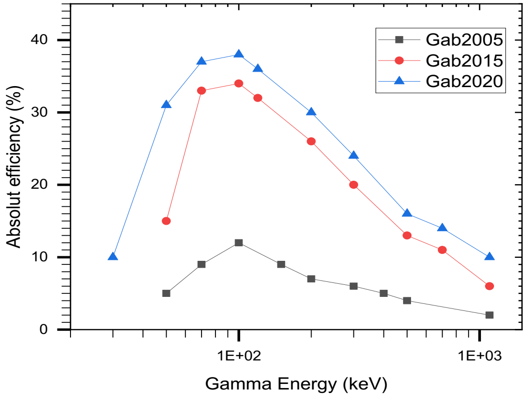
(Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyzer)

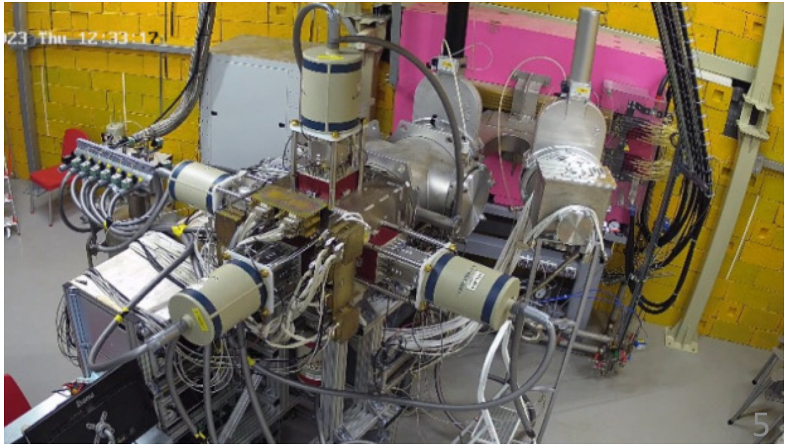
DSSD	FWHM [keV]	Thresholds [keV]
Focal plane 100x100 mm^2 128x128 strips Thickness: 500 μm	10.8±0.6 keV - 320 keV electrons; 16.5±0.8 keV - 7.92 MeV alphas	40-60
8 Tunnel 50x60 mm^2 16x32 strips Thickness: 700 μm **(CE)**	14.4±1.2 keV - 320 keV electrons 120±11 keV - 7.92 MeV alphas	60-100



5 Ge-detectors
Clover-type, HPGe,
100x100 mm, 70 mm height)
BGO-shields
A low neutron background is required!

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



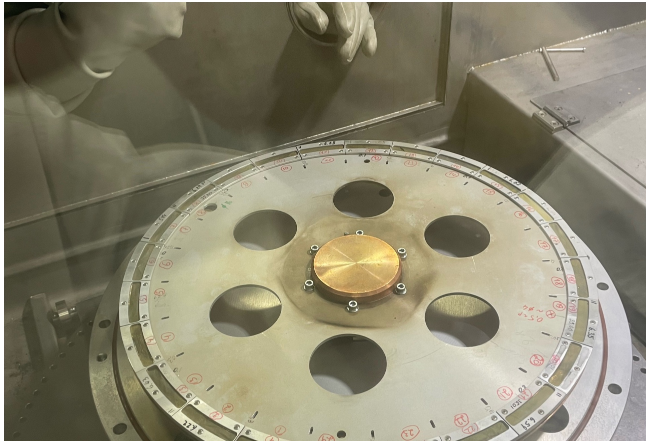


The 480 mm diameter target on GRAND

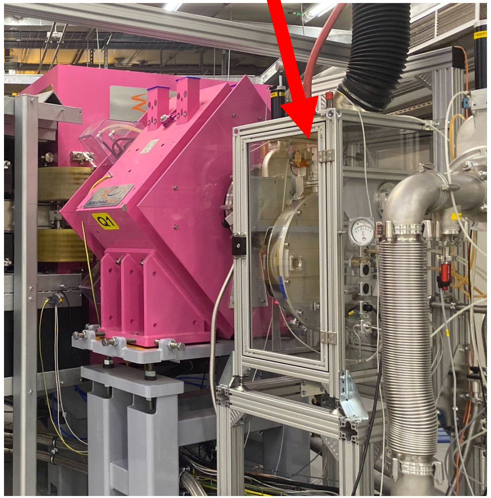
- **Year: 2025**
- **Reactions: $^{242}Pu(^{48}Ca, 3\text{-}4n)^{287\text{-}286}Fl$**
- PuO_2 target: 697±50 μg/cm^2 on 1.5 μm Ti backing
- Wheel diameter: 480 mm
- Total area: 141 cm^2
- Segments: 24
- **Beam: 5 pμA**
- Gas on separator: He

Main result:
the target is stable during several weeks of irradiation without any significant loss of the material!

Data analysis is in progress…



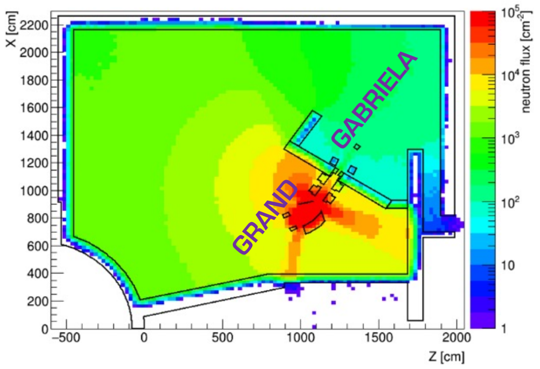
FLNR Sector #3: A.V. Sabelnikov and G.K.Vostokin



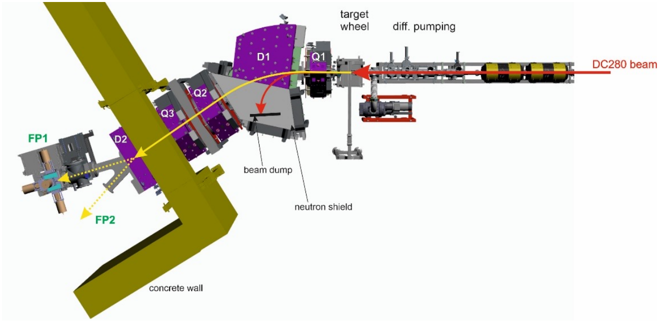
FLNR Sector #2: O.N. Malyshev, E. Teymurov and Yu. A. Popov

Neutron and Gamma Backgrounds

$^{48}Ca^{+10}$, 7 pμA (simulated!)



Measured fluxes on detectors for 4 pμA:
thermal neutron > 200 cm^{-2}
photon flux < 50 cm^{-2}



Goals:

- prevent GABRIELA setup Ge-detectors degradation
- reduce the random coincidences
- ability to use digital electronics for detectors

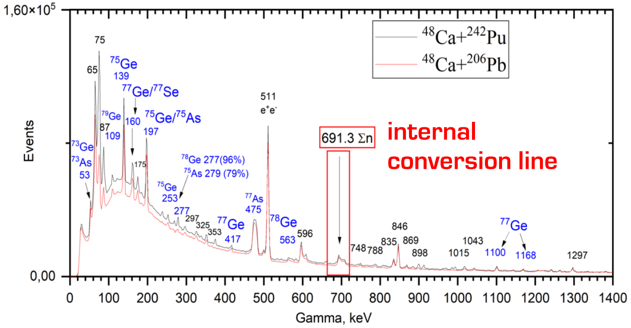
FLNR Sector #2: D.E. Katrasev, B. Sailaubekov and A.V. Isaev

Current status:

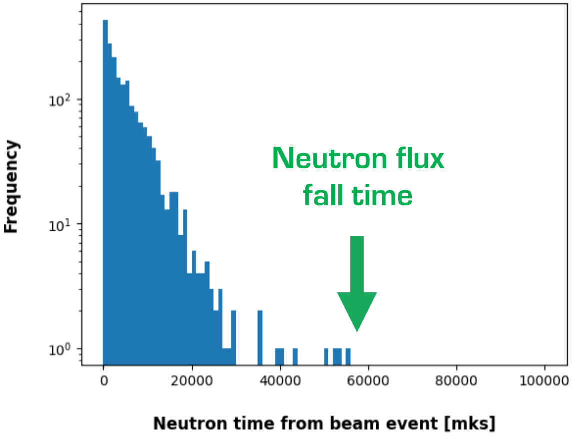
- the detection system is **partially** covered by a concrete wall
- a borated polyethylene shield near the beam stopper was added
- the Cu beam stopper was replaced with Ta (x2 reduction of neutron background)

Neutron and Gamma Backgrounds

The data from Ge-detectors of GABRIELA



1s beam modulation



7 ^{3}He counters

(7 atm, L = 0.5 m, D = 30 mm)

in moderator close to GABRIELA

4 pμA of ^{48}Ca

(~ 7 kHz per counter)

FLNR Sector #2: Yu. A. Popov

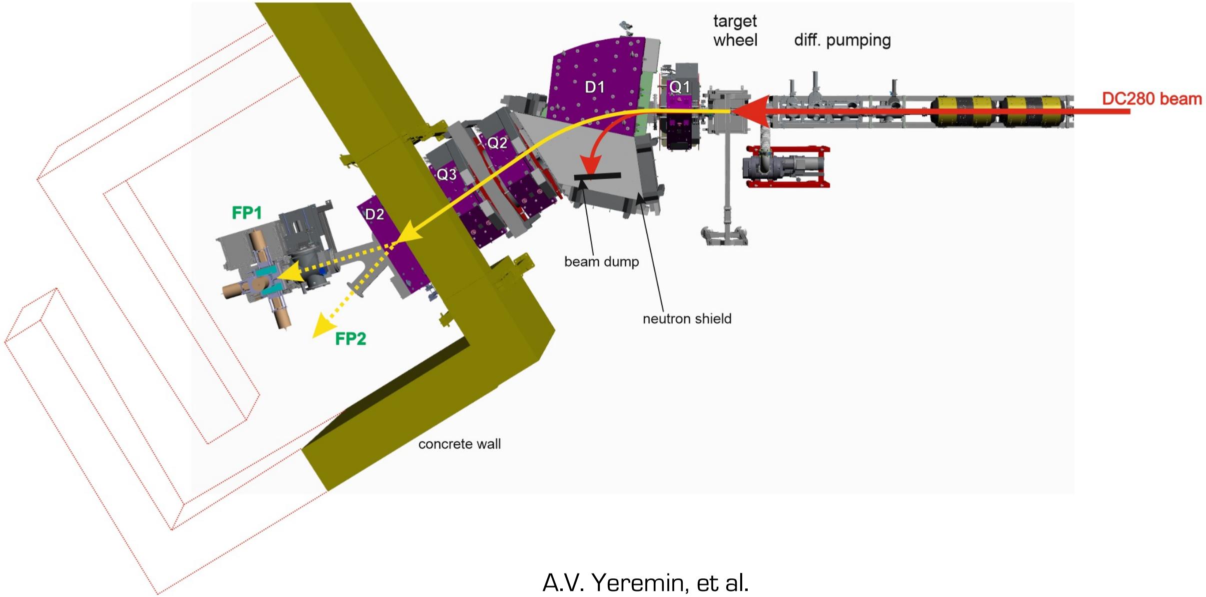
Neutron and Gamma Backgrounds

Plans:

- the detector cave is planned to be built in 2026
- creation of a more complex shield is under discussion
- cast stopper made of Cu and W alloy
- more beam diagnostics tools development are needed…

Separator **GRAND**

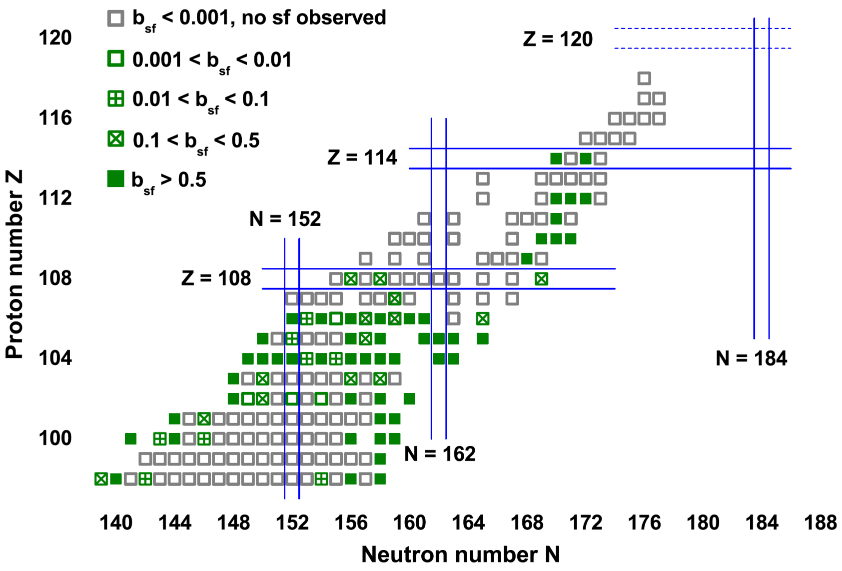
Gas-filled **R**ecoil **A**nalyzer and **N**uclei **D**etector



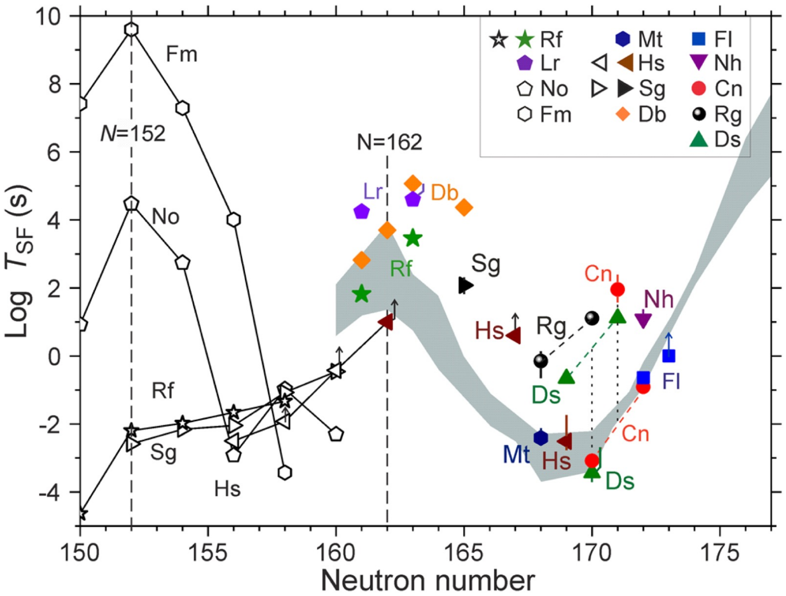
A.V. Yeremin, et al.
Universal GRAND Gas-Filled Separator: First Experimental Results.
PEPAN Letters, Vol. 21, No. 3, pp. 518–525 (2024)

Spontaneous Fission of SHE with SFiNx

- SF is a common process in the SHE region and it defines the boundaries of the existence of elements
- **The dynamic of SF is unknown in this area of nuclides, so pioneering experiments could be made…**

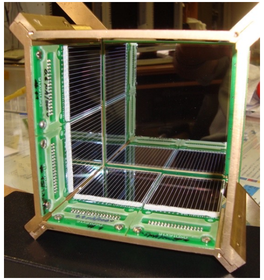


Heßberger F. P. Spontaneous fission properties of superheavy elements. Eur. Phys. J. A (2017) 53: 75



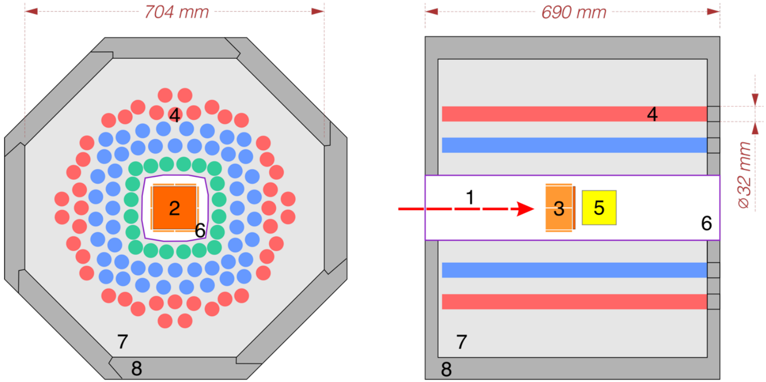
Yu. Ts. Oganessian et. al, New isotope ^{286}Mc produced in the ^{243}Am + ^{48}Ca reaction, Phys. Rev. C 106, 064306 (2022)

Spontaneous Fission of SHE with SFiNx



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

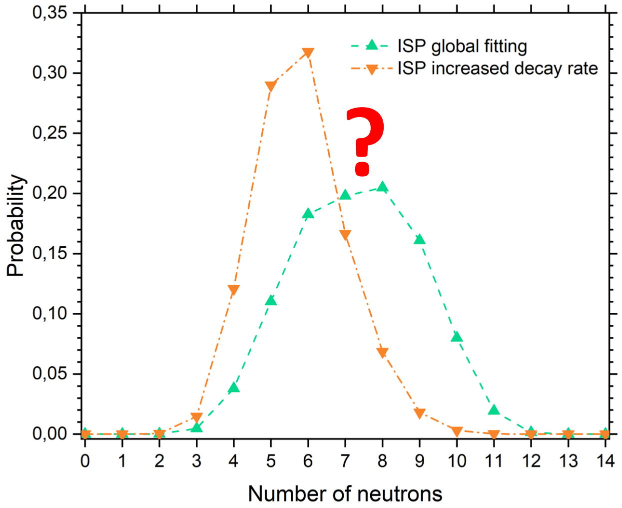
ε_n = 55±1%



The legend:

1 – evaporation residues
2 – focal-plane 128×128-strip DSSD
3 – 8 side 32×16-strip DSSD
4 – 116 ^{3}He-counters (7 atm)
5 – 9 CLLBC scintillators
6 – vacuum chamber
7 – moderator
8 – shield

^{282}Cn



Calculations with an additional version of the ISP model made by BLTP JINR: A. V. Andreev, T. M. Shneidman and A. Rahmatinejad

Spontaneous Fission of SHE with SFiNx

FLNR Design Bureau: M.A. Bychkov
FLNR Sector #2: A.V. Isaev and A.I. Svirikhin

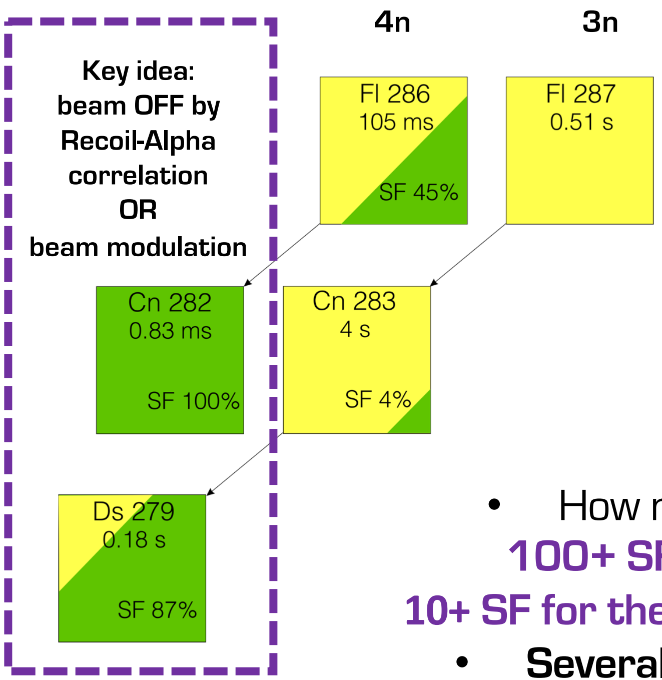
480 mm rotating target
and 5 pμA of ^{48}Ca
SHE Factory, April 2024
1 SF/s of ^{252}No

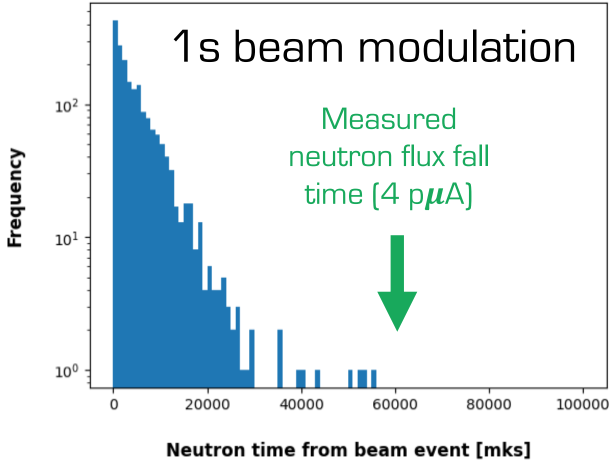
–

1.5 pμA of ^{48}Ca, December 2022
2 Fl decays/day

Plans: the first data about SF dynamic for SHE nuclei

^{242}Pu + ^{48}Ca





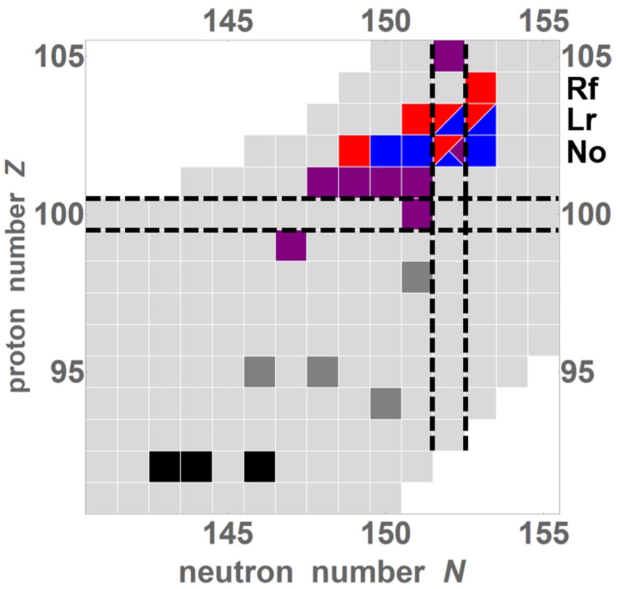
- How much statistics is needed?

100+ SF for neutron multiplicity
10+ SF for the average number of neutrons

- **Several** isotopes in **one** experiment

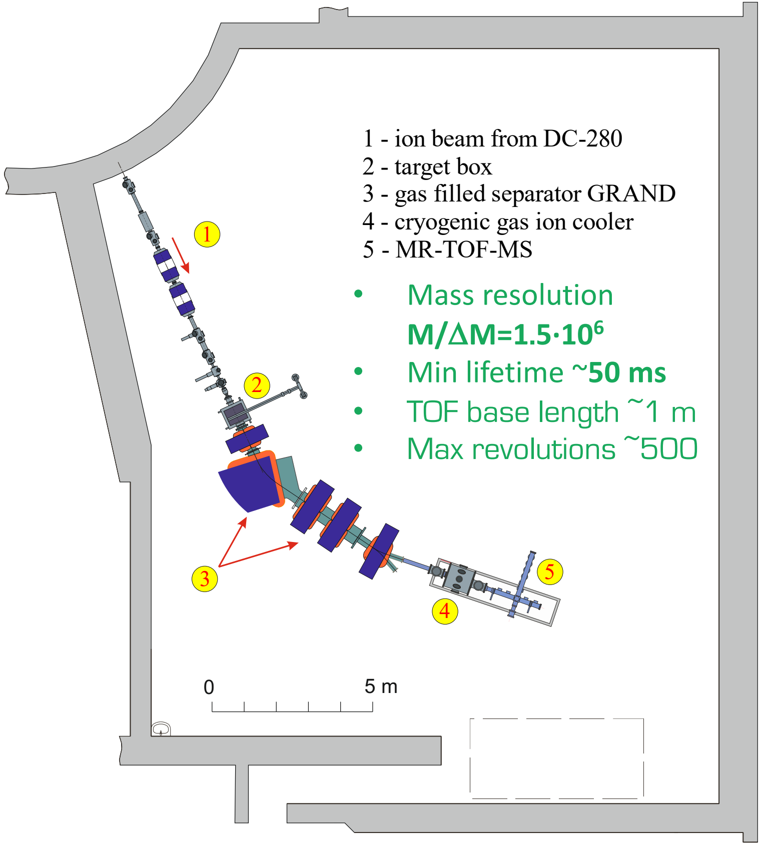
SHE Mass Measurements

Part of the nuclear chart, showing direct mass spectrometry carried out with the **RIKEN MR-ToF MS**, **TRIGATRAP**, and **SHIPTRAP**.



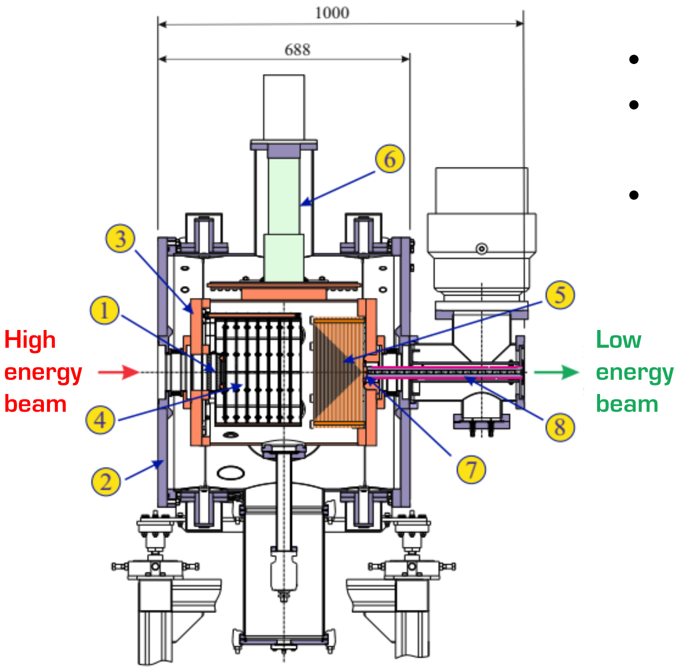
O. Kaleja, et al. Direct high-precision mass spectrometry of superheavy elements with SHIPTRAP. Phys. Rev. C 106, 054325 (2022)

FLNR mass spectrometer



- Mass resolution **$M/\Delta M=1.5\cdot10^6$**
- Min lifetime ~**50 ms**
- TOF base length ~1 m
- Max revolutions ~500

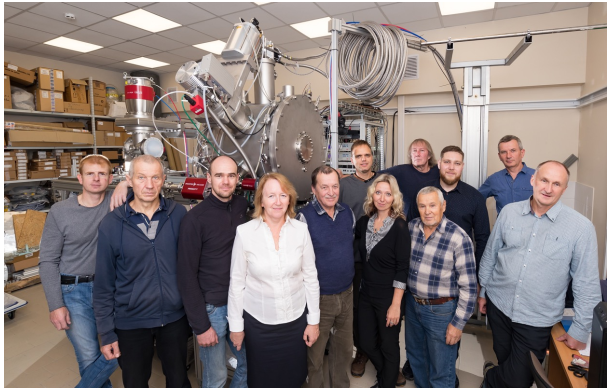
SHE Mass Measurements

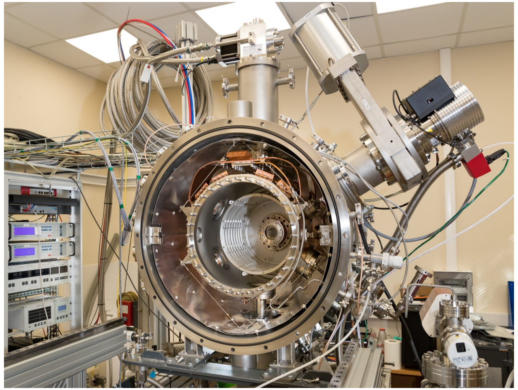


Legend: 1 – entrance window (3 microns of mylar); 2 – warm vacuum chamber; 3 – cold chamber; 4 – cylindrical cage with constant voltage electrodes; 5 – funnel of 76 electrodes; 6 – cryo refrigerator head; 7- Laval nozzle; 8 – gas-filled radio frequency quadrupole guide.

Cryogenic gas ion cooler motivation:

- Not influenced by any physical or chemical environment properties
- Significantly shorter separation and extraction time in comparison to solid or liquid states ion catchers (~**30-40 ms**)
- Extraction efficiency: ~**30%** (for ^{254}No with Q=2)





FLNR Sector #4: A.M. Rodin, et al.

Gas catcher status:

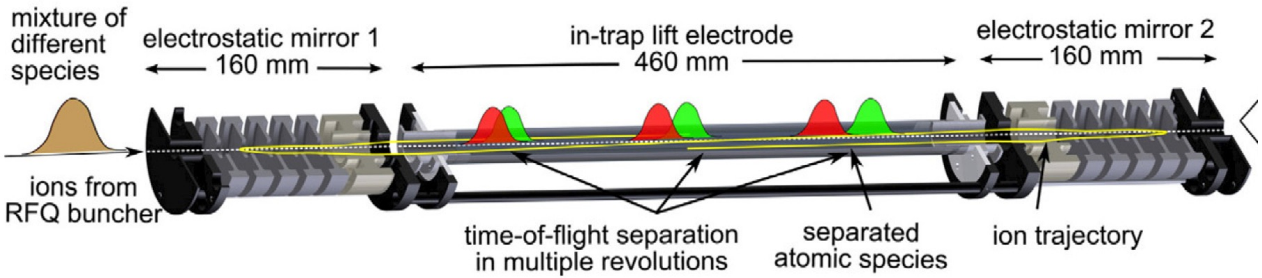
- Mechanical design, vacuum, gas inlet, cryogenic, control system are done.
- Offline testing is in progress, the preliminary efficiency is ~50% (at room temperature)

SHE Mass Measurements

M.I. Yavor, et al. Development of a mass spectrometer for high-precision mass measurements of superheavy elements at JINR. JINST 17, P11033 (2022)

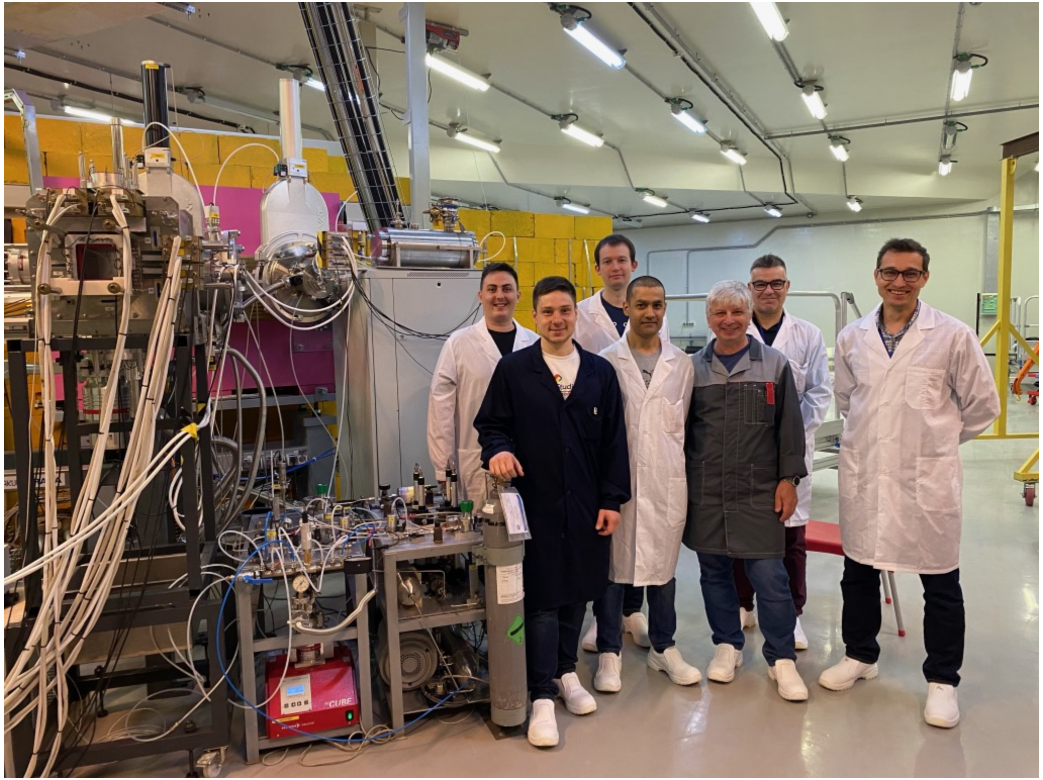
MR-TOF-MS status:

- Ion-opting system calculation **done**
- Draft mechanical design **done**
- Development of design documentation for mass-analyzer **done**
- Full design documentation for the spectrometer **will be ready at the end of 2026**
- The stand of the ion source on fullerene clusters with a mass filter **will be ready in the middle of 2026**



MR-TOF common scheme. T.Yamaguchi, H.Koura,Yu.A.Litvinov, M.Wang. Masses of exotic nuclei. Progress in Particle and Nuclear Physics 120 (2021) 103882.

Chemistry of SHE on GRAND

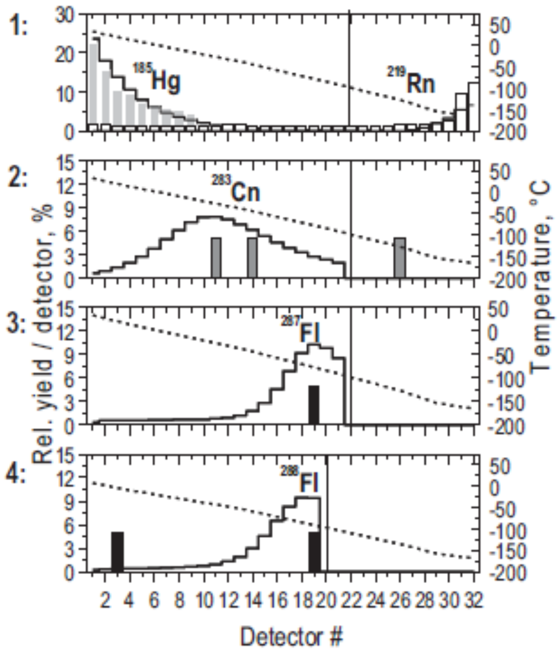


FLNR Sector #3: N.V. Aksenov, et al.

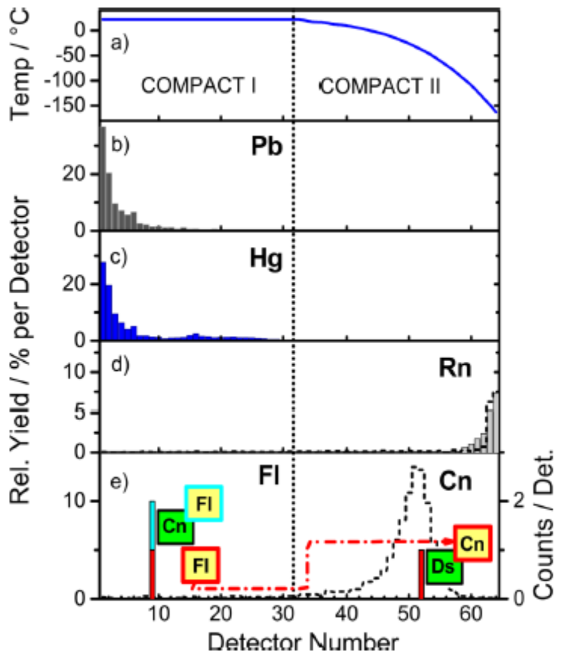
- **Relativistic effects** can significantly affect the chemical properties of superheavy elements
- Theoretical calculations show that the volatility and chemical reactivity of SHEs can **differ from** the properties of the nearest light **homologues**
- Experimental studies of chemical properties are complicated – SHE nuclei have very short half-lives and low formation cross-sections
- The most-used experimental method for studying the SHE's adsorption properties is **gas chromatography**

Chemistry of SHE on GRAND

Is flerovium a metal or a noble gas?



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

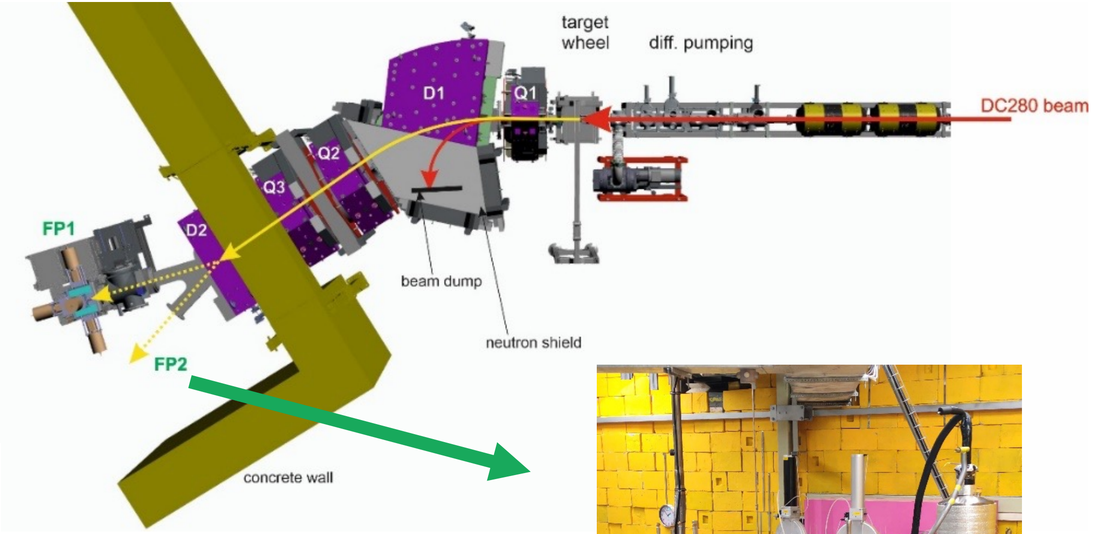


A. Yakushev et al.,
Inorg. Chem. 53, 1624 (2014)

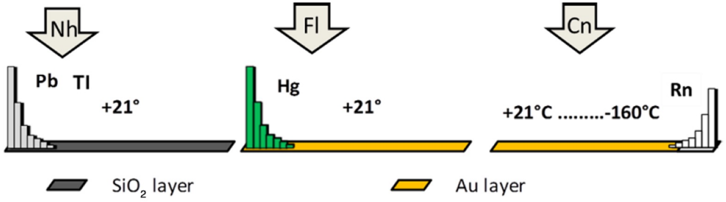
From the distributions of atoms over the detectors:

- **adsorption** properties of Cn and Fl
- thermodynamic characteristics of Cn and Fl compared with their light homologs Hg and Pb
- experimental determination of the influence of **relativistic effects** on the chemical properties of the heaviest elements
- degree of compliance with the chemical behavior of the SHE with the law of periodicity of properties

Chemistry of SHE on GRAND

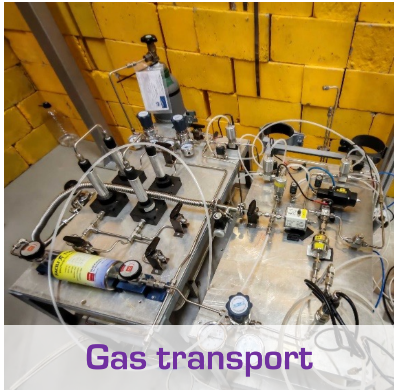


Gas adsorption thermochromatography method

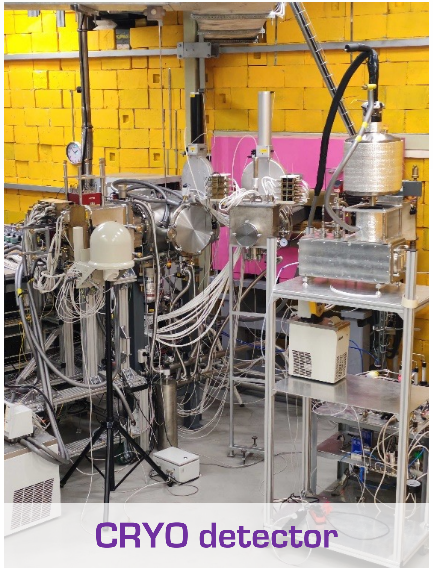


Predicted adsorption positions (schematic) of Cn, Nh, and Fl, with respect to their homologs and Rn, on the combined SiO_2/gold surface detector system in gas-phase chromatography experiments.

V. Pershina. Relativistic effects on the electronic structure of the heaviest elements. Is the Periodic Table endless?. Comptes Rendus. Chimie, Variations around the Periodic Table, Volume 23 (2020) no. 3, pp. 255-265



Gas transport



CRYO detector

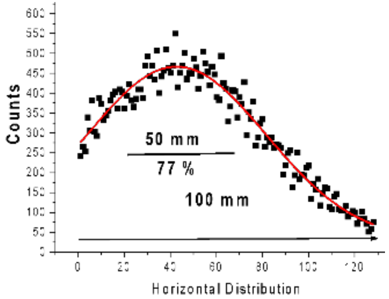
Chemistry of SHE on GRAND

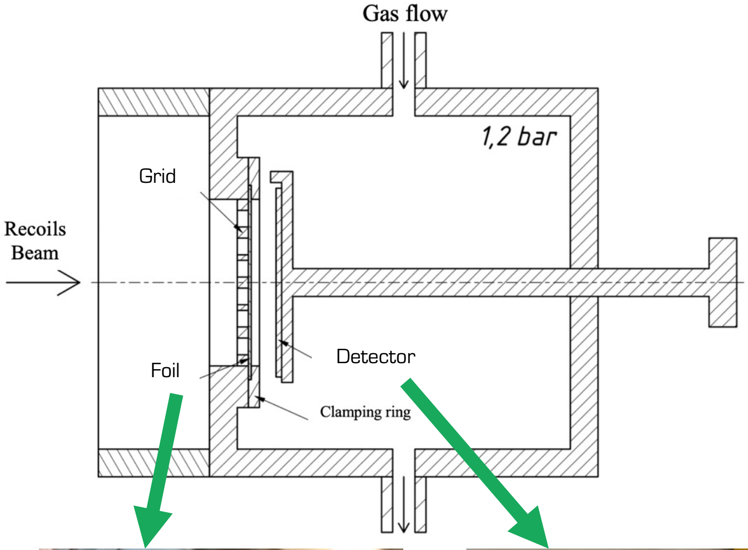
- Separating foil thickness optimization
- Grid geometry optimization
- Optimal gas pressure
- Optimal Ar/He proportion

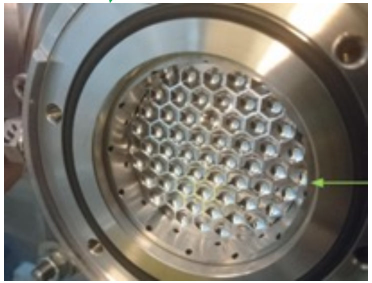
Test reactions:

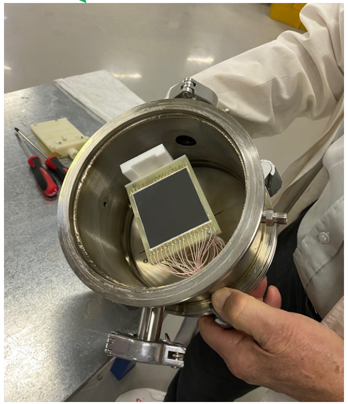
$^{208}\mathrm{Pb}(^{48}\mathrm{Ca}, 2n)^{254}\mathrm{No}$ ($E_{ER} \approx 40$ MeV)

$^{144}\mathrm{Sm}(^{40}\mathrm{Ar}, xn)^{184\text{-}n}\mathrm{Hg}$ ($E_{ER} \approx 47$ MeV)

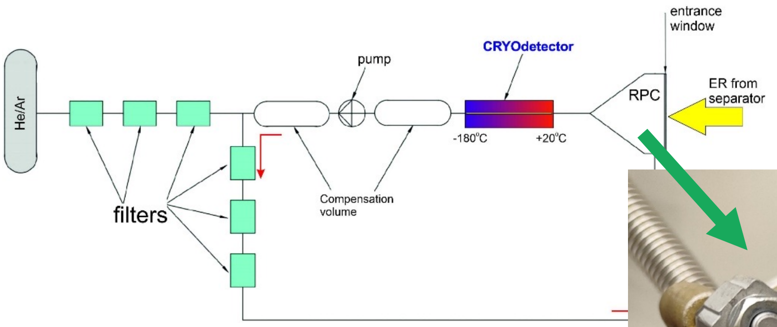




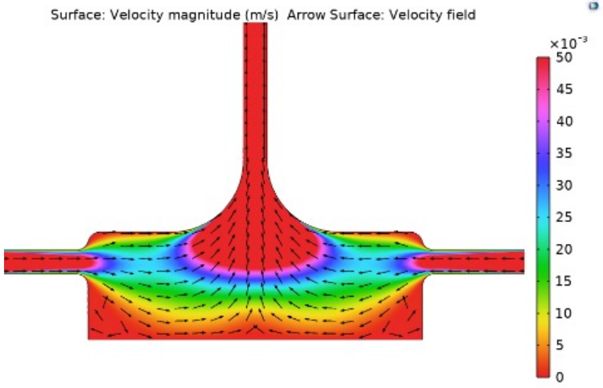




Chemistry of SHE on GRAND



V = 44,3 cm^3



Test reactions:

$^{208}Pb(^{48}Ca, 2n)^{254}No$ ($E_{ER} \approx 40$ MeV)

$^{144}Sm(^{40}Ar, xn)^{184-n}Hg$ ($E_{ER} \approx 47$ MeV)

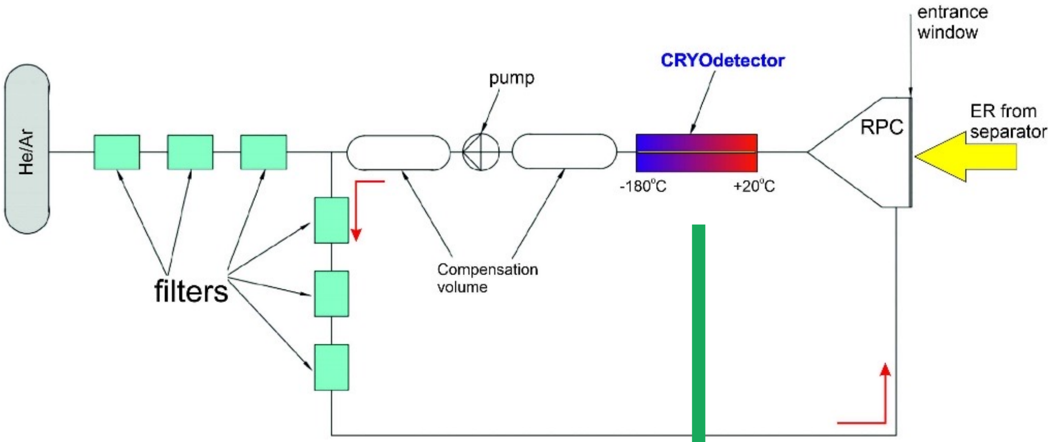
Total gas renewal time: 1.6 s

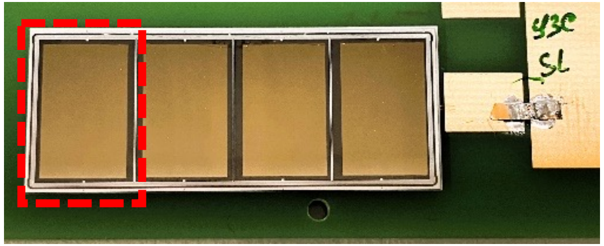
Hg transport time: 0.2 s!

^{287}Fl $T_{1/2}$: 0.36 s

Chemistry of SHE on GRAND

Gas adsorption thermochromatography method

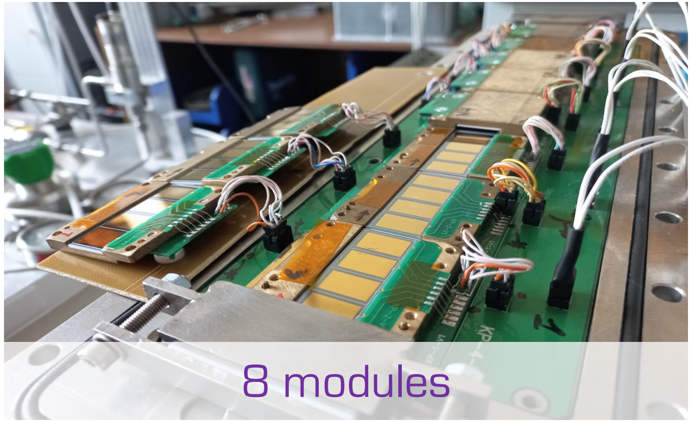




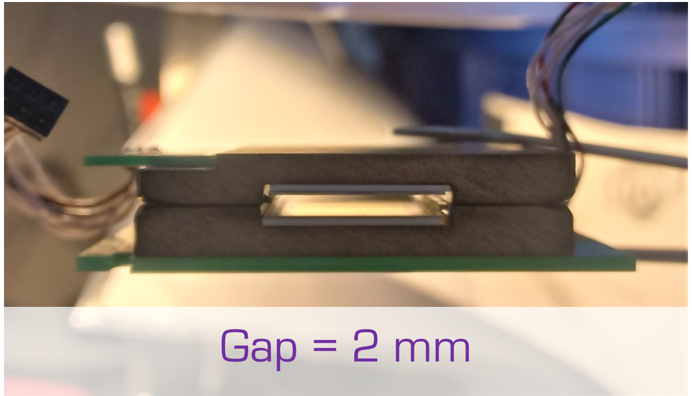
S_{Si} = 20x10 mm²

S_{gold} ≈ 95%

Detection modules with gold surface

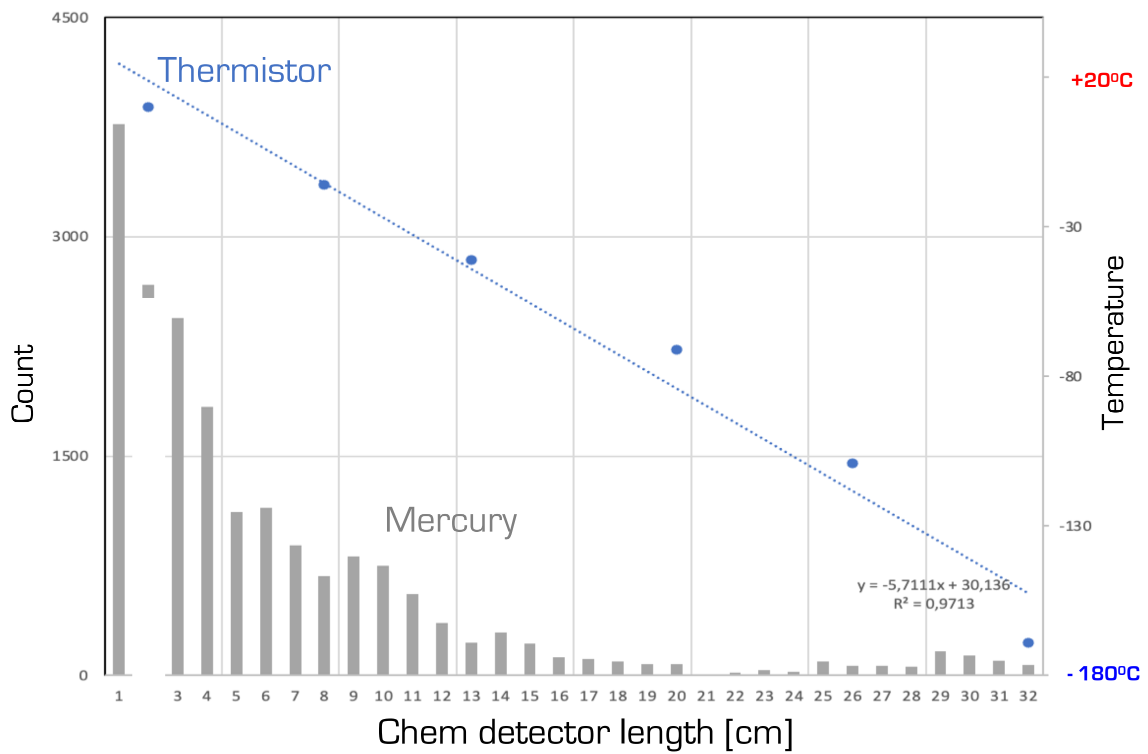


8 modules



Gap = 2 mm

Chemistry of SHE on GRAND



New LN cooling system

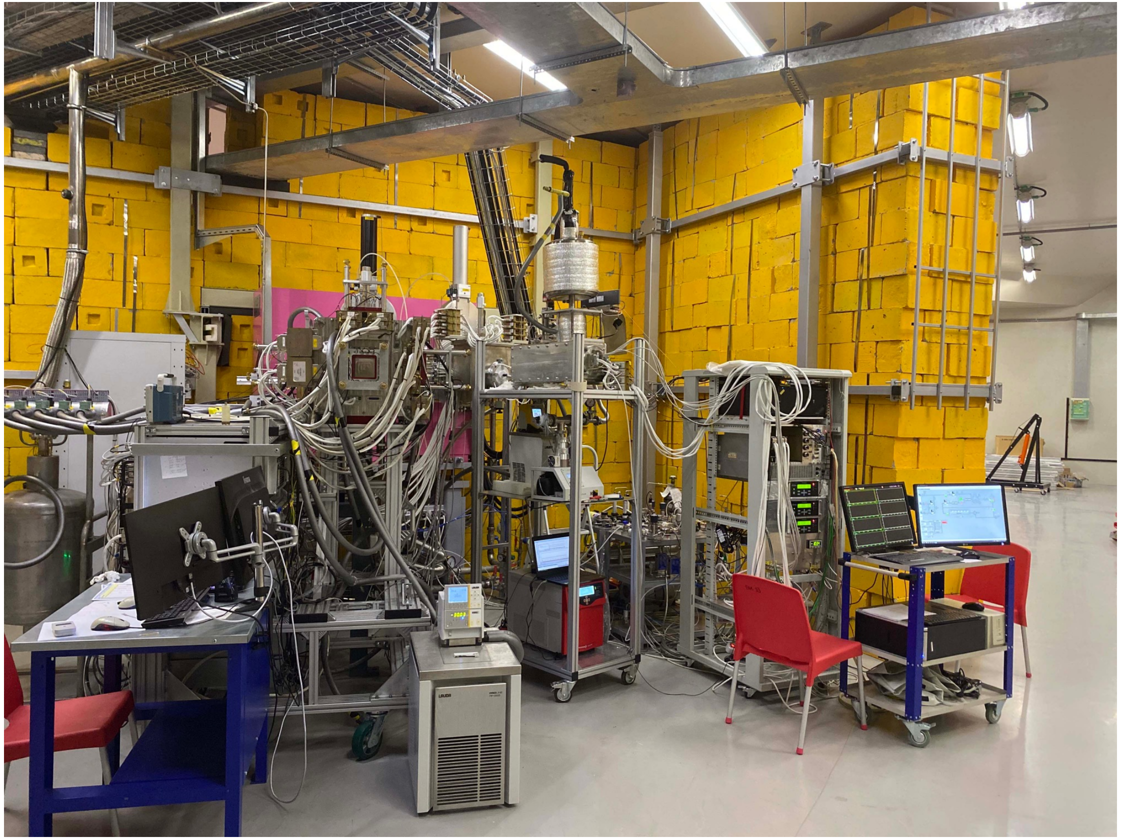
Chemistry of SHE on GRAND

$^{242}Pu(^{48}Ca, 3n)^{287}Fl$

$T_{1/2}$ ~ 0.36 s, σ_{max} = 10 pb
h_t=0.7 mg/cm^2, $Ø_t$ = 480 mm
ε_{GRAND}= 0.4, I_{beam}= 5 pμA
several Fl(Cn) per day $\times\ \varepsilon_{CRYO}$

December 2022:
Target – 240 mm, 0.7 mg/cm^2
Mean beam intensity – 2 pμA
Integral – 1.6×10^{19}
Result: 2 chains

June 2025:
Target – 480 mm
Mean beam intensity – 5 pμA
Integral – 3.4×10^{19}
Preliminary Result: 6 chains

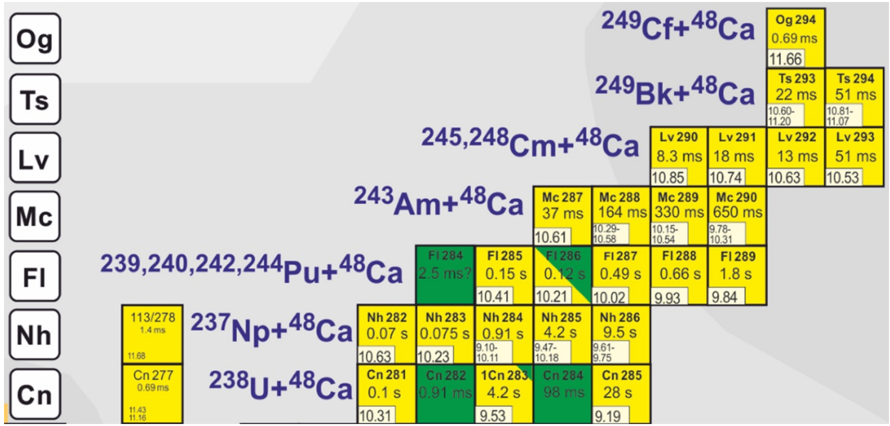


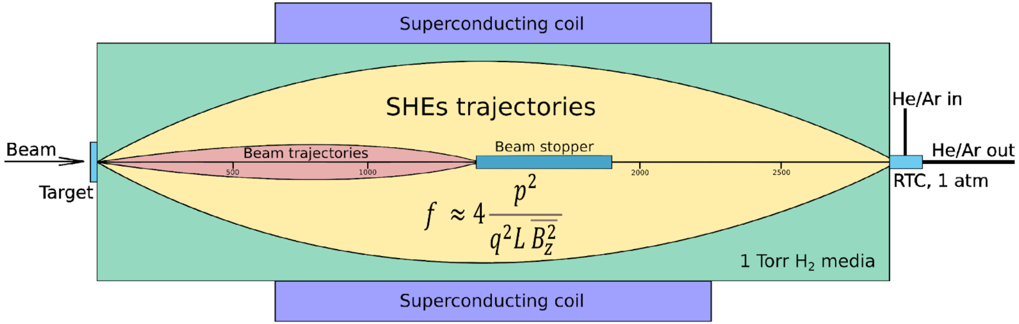
Chemistry of SHE with GASSOL

GASSOL – a new solenoidal pre-separator for studies of chemical properties of superheavy elements

Motivation and purpose:

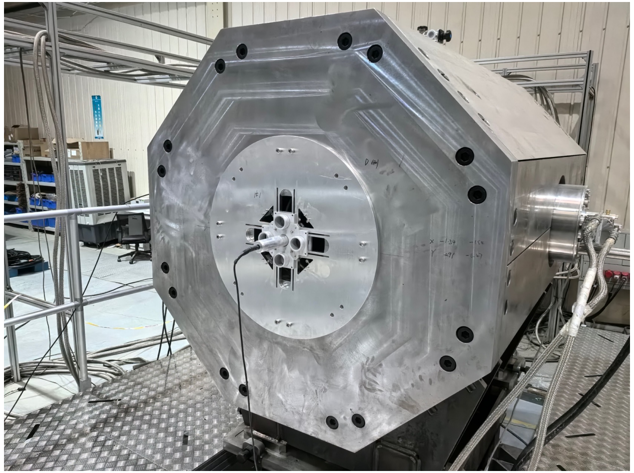
- Pre-separation is needed – high beam intensity or high background affects the quality of the experiment
- One of the most important things is the time of transport
- Time of transport depends on recoil transfer chamber size (depending on the image size of ER in the focal plane of the pre-separator
- We need a small image size – a gas-filled solenoid seems like a good option!
- With the GASSOL it will be possible to move SHE chemistry research to the area of ms half-lives (115-118 elements)





Chemistry of SHE with GASSOL

- Magnet produced by Xi'an Superconducting Magnet Technology Co. LTD (Xi'an, China)
- **First cool down finished in April 2025, 4K achieved**
- **Magnetic tests of the separator are currently underway**
- Delivery is planned for September 2025 (but several delays happened)
- Technical systems are under construction
- The testing procedure developed and two detector assemblies are being produced



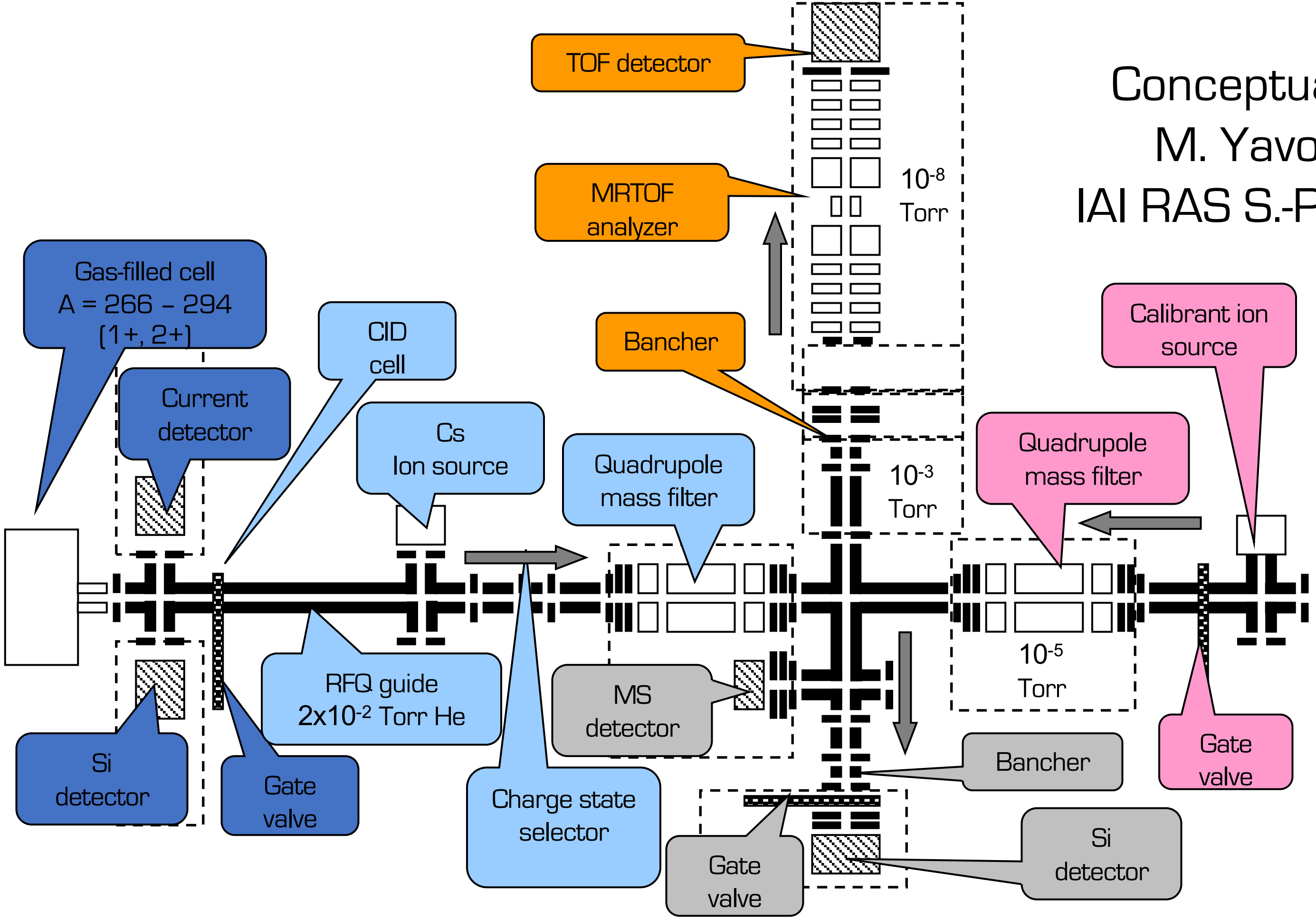
Conclusion

Setup	Current Status
DC-280	• Stable 5 pμA of ^{48}Ca beam on experiment target with stable energy.
GRAND	• ^{242}Pu target tested (D = 480 mm; the target is stable on 5 pμA of ^{48}Ca for several weeks). • First results on the chemical detector. • Neutron and gamma background suppression on GRAND separator. • Preparing to SHE mass measurements (cryogenic gas ion cooler created; MR-TOF mass analyzer is under design). • Preparation of Fl and Mc spectroscopy on GRAND (with GABRIELA and SFiNx detector systems).
DGFRS-2	• Preparations for the synthesis of 119 and 120 elements are underway.
GASSOL	• Preparation to install GASSOL separator (magnet tests in progress).

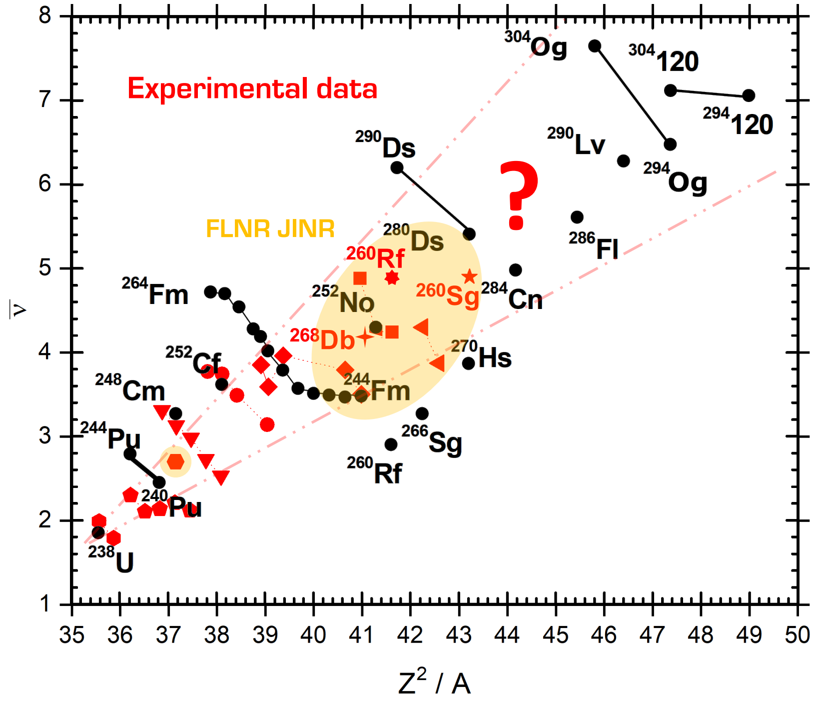
Thank you for your attention!

MR-TOF-MS

Conceptual design
M. Yavor et al.
IAI RAS S.-Petersburg



Spontaneous Fission



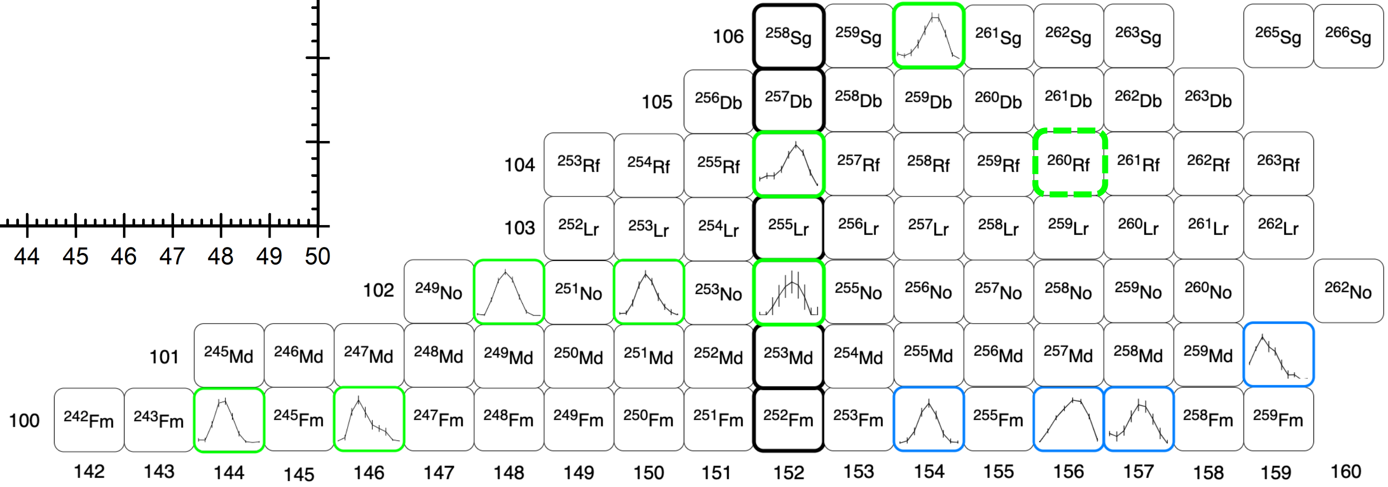
Theoretical calculations (●)

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

Shapes of the Prompt Neutron Multiplicity Distributions

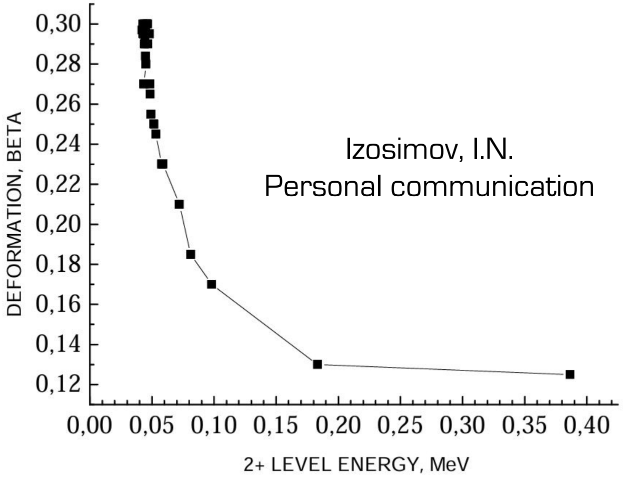
SHELS separator (FLNR)

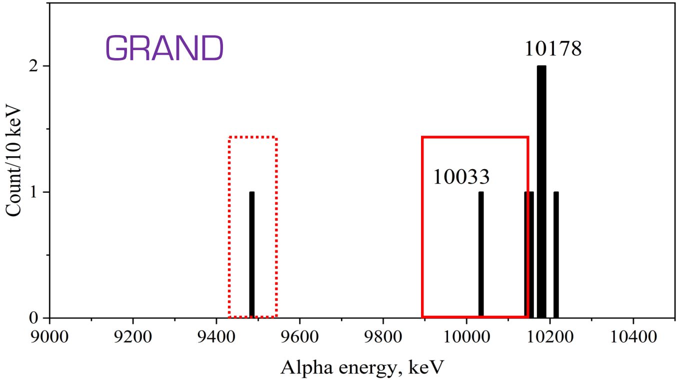
In progress, 2025

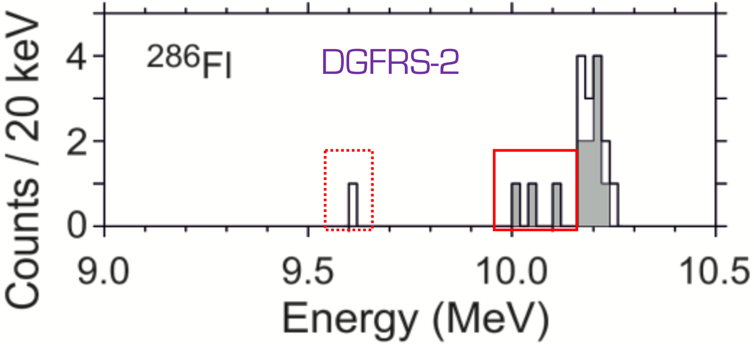


Fine Structure in the Alpha Decay

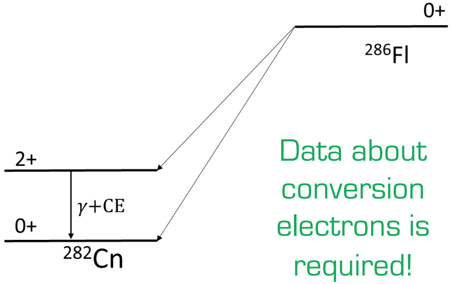
Investigation of fine structure in the alpha decay of even-even SHE nuclei could provide direct information about the deformation of the nucleus shape







Reaction: ^{242}Pu(^{48}Ca, 4n)^{286}Fl
Target D: 480 mm
Max cross section: ~ 5 pb
^{48}Ca beam: ~ 5 pμA
Transmission: ~40 %
Yield: a few ^{286}Fl per day



Data about conversion electrons is required!

Yu. Ts. Oganessian et. al, Investigation of ^{48}Ca-induced reactions with ^{242}Pu and ^{238}U targets at the JINR Superheavy Element Factory, PRC 106, 024612 (2022)

GABRIELA and SFiNx last 3 years' publications

1. M. Forge, et al. First experimental measurement of spin splitting and evidence for a second 0^+ state in ^{254}No, **submitted to Phys. Rev. Lett.**
2. P. Brionnet, et al. Structure studies of ^{257}Db through combined alpha, gamma and internal-conversion-electron spectroscopy, **submitted to Physical Review C.**
3. A.V. Isaev, et al. The SFiNx detector system (current status), **PEPAN Letters** 22 №2 300-303 (2025).
4. H.M. Devaraja, et al. Systematic studies to produce heavy above-target nuclides in multinucleon transfer reactions, **Physical Letters B** 862 139353 (2025).
5. A.A. Kuznetsova, et al. Properties of Radioactive Decay of the New Nucleus ^{227}Pu, **PEPAN Letters**, 22, № 2(259). C.244–253 (2025).
6. R.S. Mukhin, et al. Prompt neutron emission in ^{250}No spontaneous fission associated with ground and isomeric states decay, **Chinese Physics C** 48 №6 064002 (2024).
7. A.V. Yeremin, et al. GRAND Universal Gas-Filled Separator: First Experimental Results, **PEPAN Letters** 21 3(254) 647–659 (2024).
8. A. Rahmatinejad, et al. Evolution of fission properties in Fermium region, **International Journal of Modern Physics E** 2441018 (2024).
9. K. Kessaci, et al. Cascade of high-K isomers in ^{255}No, **Physical Review C** 110 054310 (2024).
10. R. S. Mukhin, et al. Prompt neutron multiplicity from spontaneous fission of ^{244}Fm, **Eur. Phys. J. A** 60 223 (2024).
11. R. S. Mukhin, et al. Analysis of the shape of multiplicity distributions of prompt neutrons emitted in spontaneous fission, **J Radioanal Nucl Chem** 333, 1559–1564 (2024).
12. M. Forge, et al. New results on the decay spectroscopy of ^{254}No with GABRIELA@SHELS, **Journal of Physics Conference Series** 2586 012083 (2023).
13. A.V. Isaev, et al. Structure of the prompt neutron multiplicity distribution in the spontaneous fission of ^{256}Rf, **Physics Letters B** 843 138008 (2023).
14. R. Chakma, et al. Investigation of isomeric states in ^{255}Rf, **Physical Review C** 107, 014326 (2023).