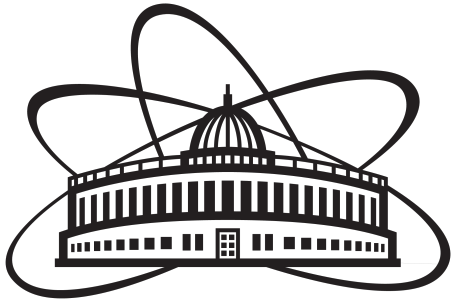
Flerov Laboratory of Nuclear Reactions, JINR



Prompt Neutron Emission From Spontaneous Fission of Superheavy Elements

Andrey Isaev

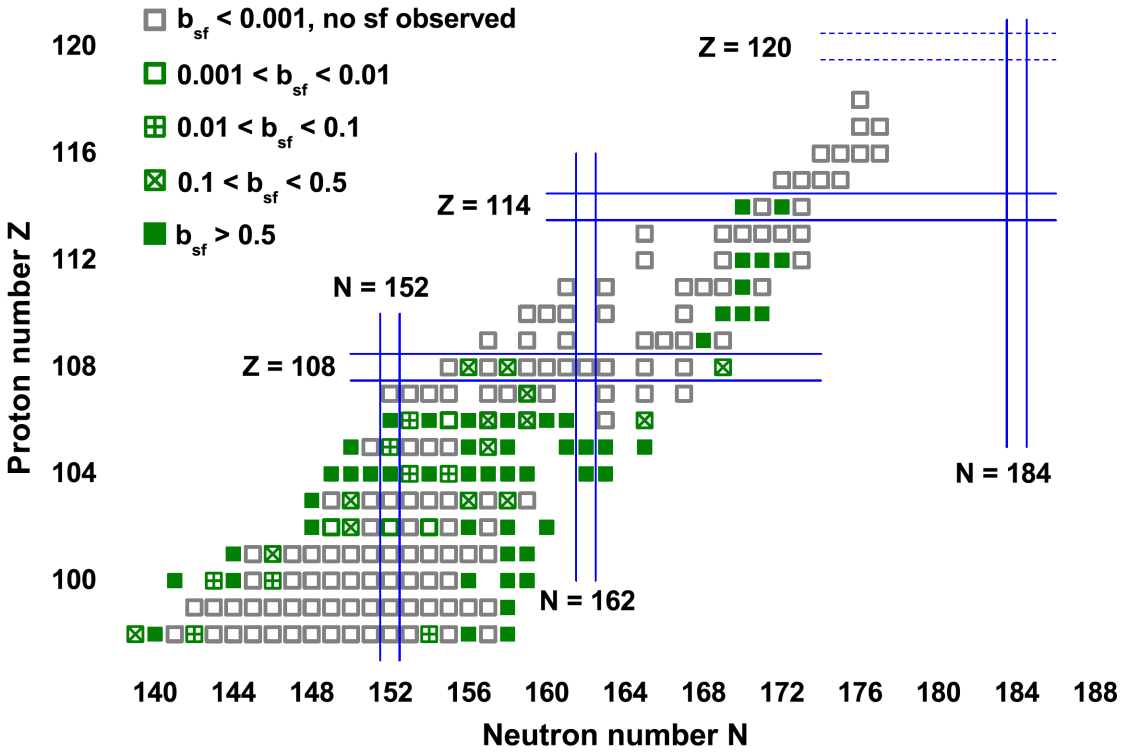
PhD, SHELS Separator Group Leader

ISINN-32

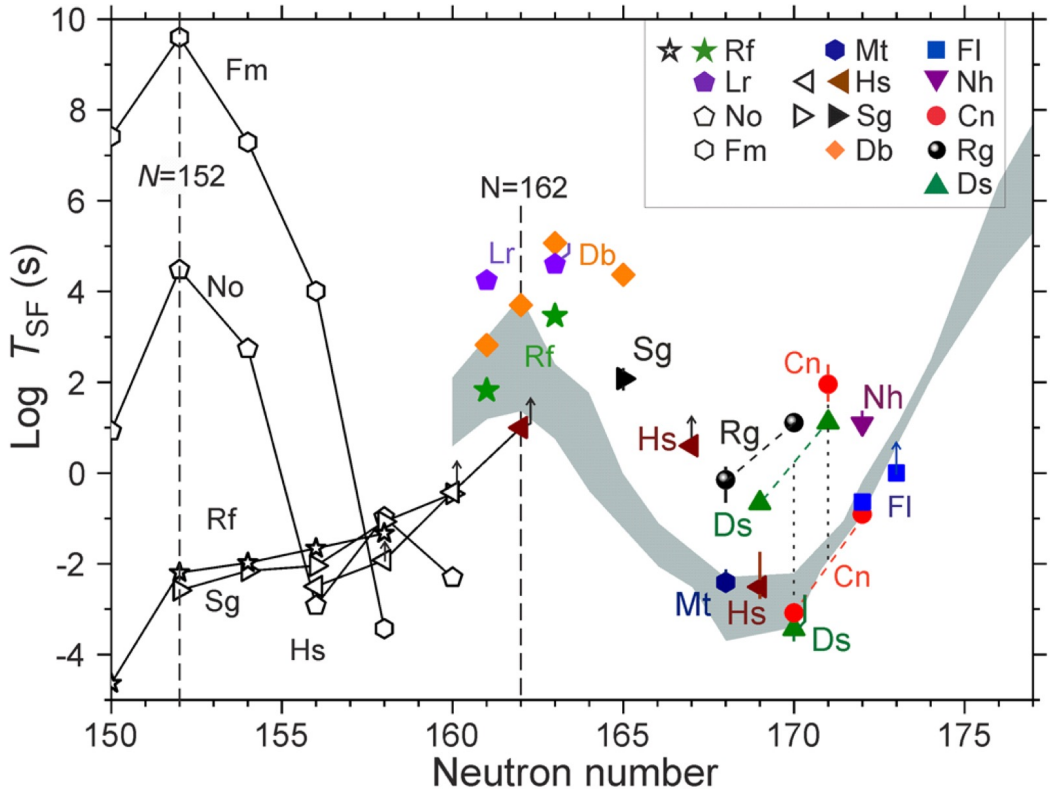
24 – 30 May 2026, JINR, Dubna, Russia

Spontaneous Fission

- SF is a common process in the SHE region and it defines the boundaries of the existence of elements
- **Fission dynamics remain unknown for SHE nuclides, opening the door for pioneering experiments…**

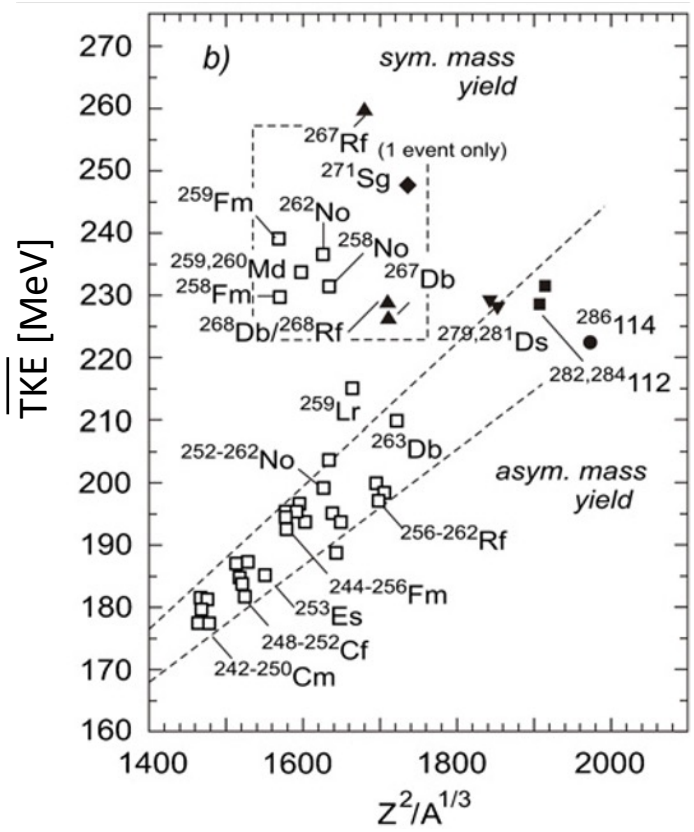


Heßberger F. P. Spontaneous fission properties of superheavy elements. Eur. Phys. J. A (2017) 53: 75

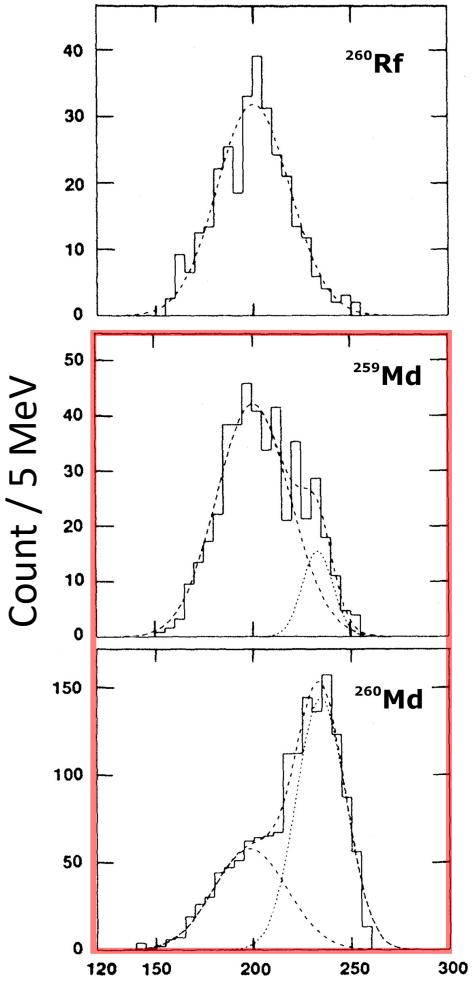


Yu. Ts. Oganessian et. al, New isotope ^{286}Mc produced in the ^{243}Am + ^{48}Ca reaction, Phys. Rev. C 106, 064306 (2022)

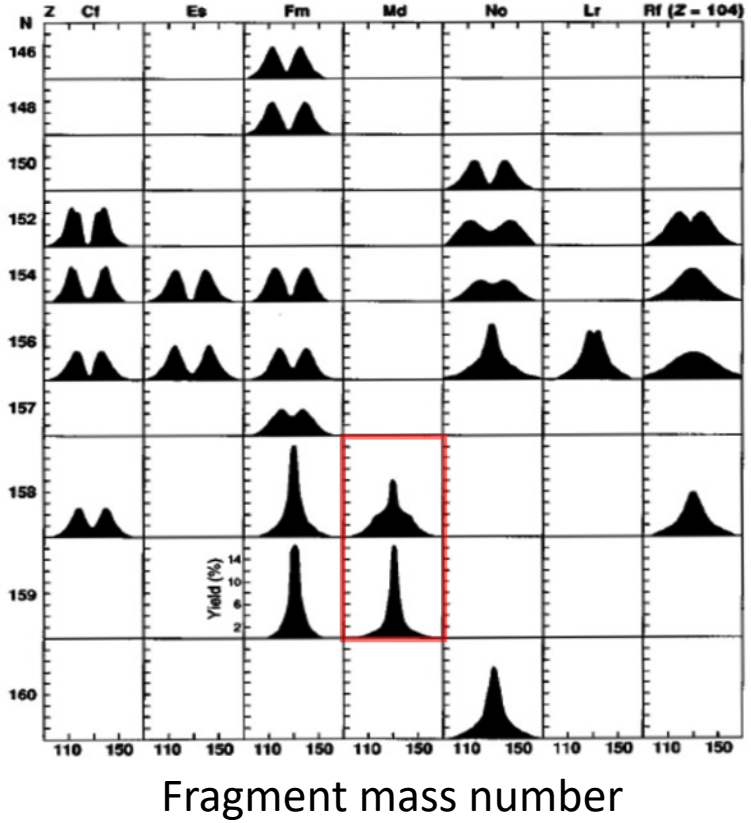
Fission Modes



Oganessian Yu. Ts.
Heaviest nuclei from ^{48}Ca-induced reactions
J. Phys. G: Nucl. Part. Phys. 34 (2007) R165–R242



Hulet E. K. et al.
Spontaneous fission properties of ^{258}Fm, ^{259}Md, ^{260}Md, ^{258}No, and ^{260}104: Bimodal fission
PRC 40/2 (1989) P. 770–784



Hoffman D. C., Lane M. R.
Spontaneous fission
RCA 70/71 (1995) P. 135–146

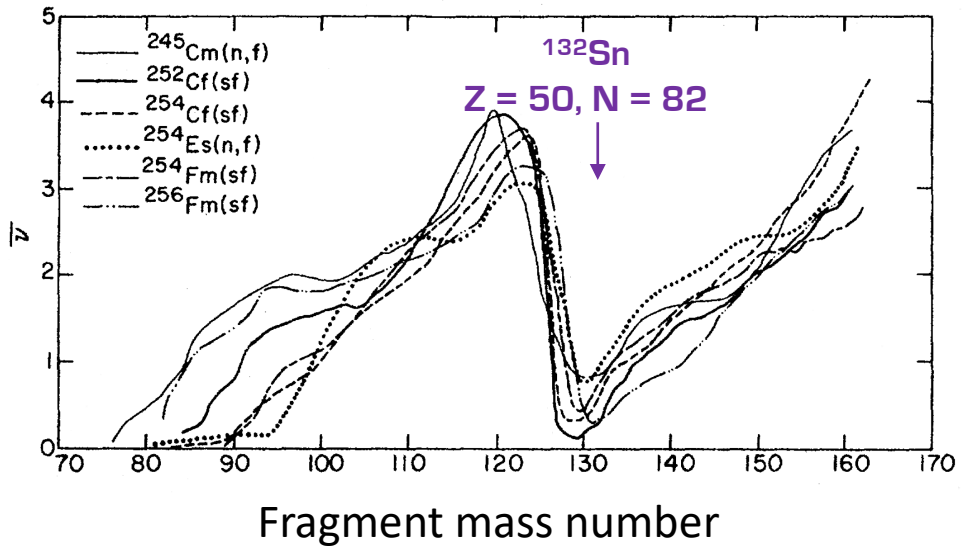
Prompt Neutrons

- Fission fragments can remove their excitation by emitting a certain number of neutrons
  - The number of emitted neutrons depends on the fragment excitation
- The multiplicity of prompt neutrons provides valuable information about the dynamics of the fission process

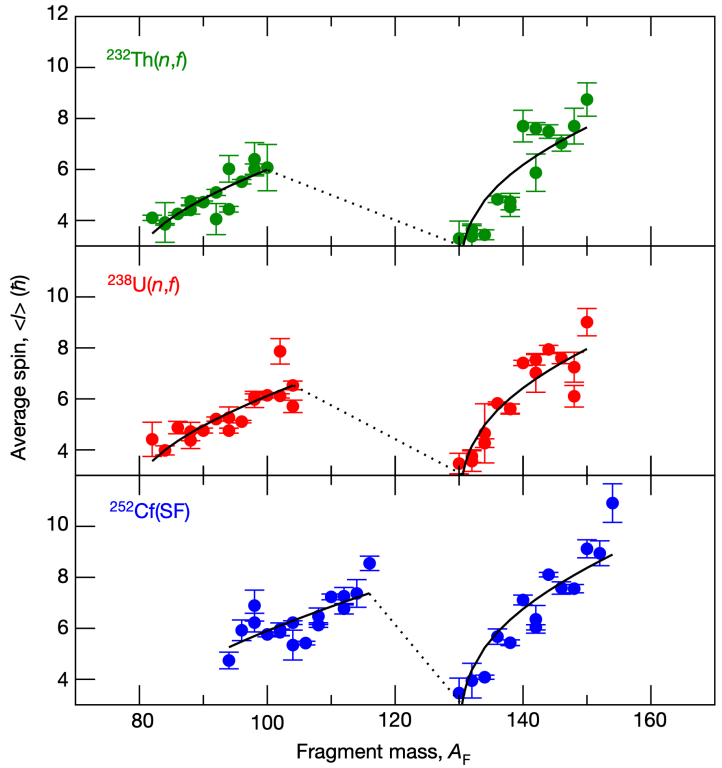
Different forms of energy (in MeV) released during SF of nuclei

Isotope	Kinetic Energy	Excitation Energy		Radioactive Decay		
		n	γ	β	γ	$\bar{\nu}_e$
^{256}Fm	198	32	8	8	8	12
^{252}Cf	186	31	7	7	7	10

Gangrskii Yu. P., Markov B. N., Perelygin V. P.
Registration and spectrometry of fission fragments.
Moscow: Energoatomizdat (1992), 312 p

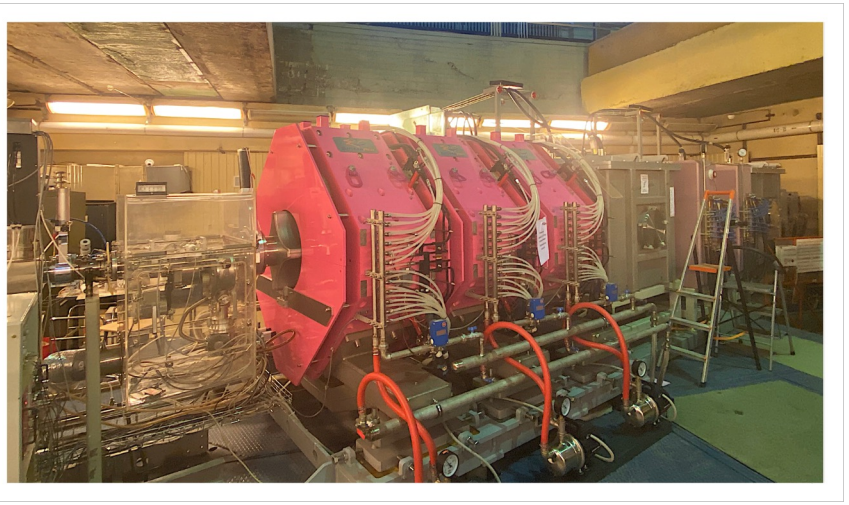


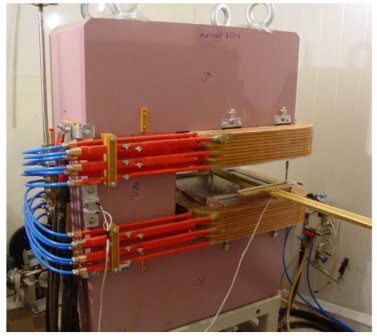
Gindler J.
Dependence of neutron yield on
fragment mass for several low-energy fissioning systems
PRC 19/5 (1979) P. 1806–1819



Wilson, J.N., Thisse, D., Lebois, M. et al.
Angular momentum generation in nuclear fission.
Nature 590, 566–570 (2021).

Separator for Heavy Element Spectroscopy – SHELS





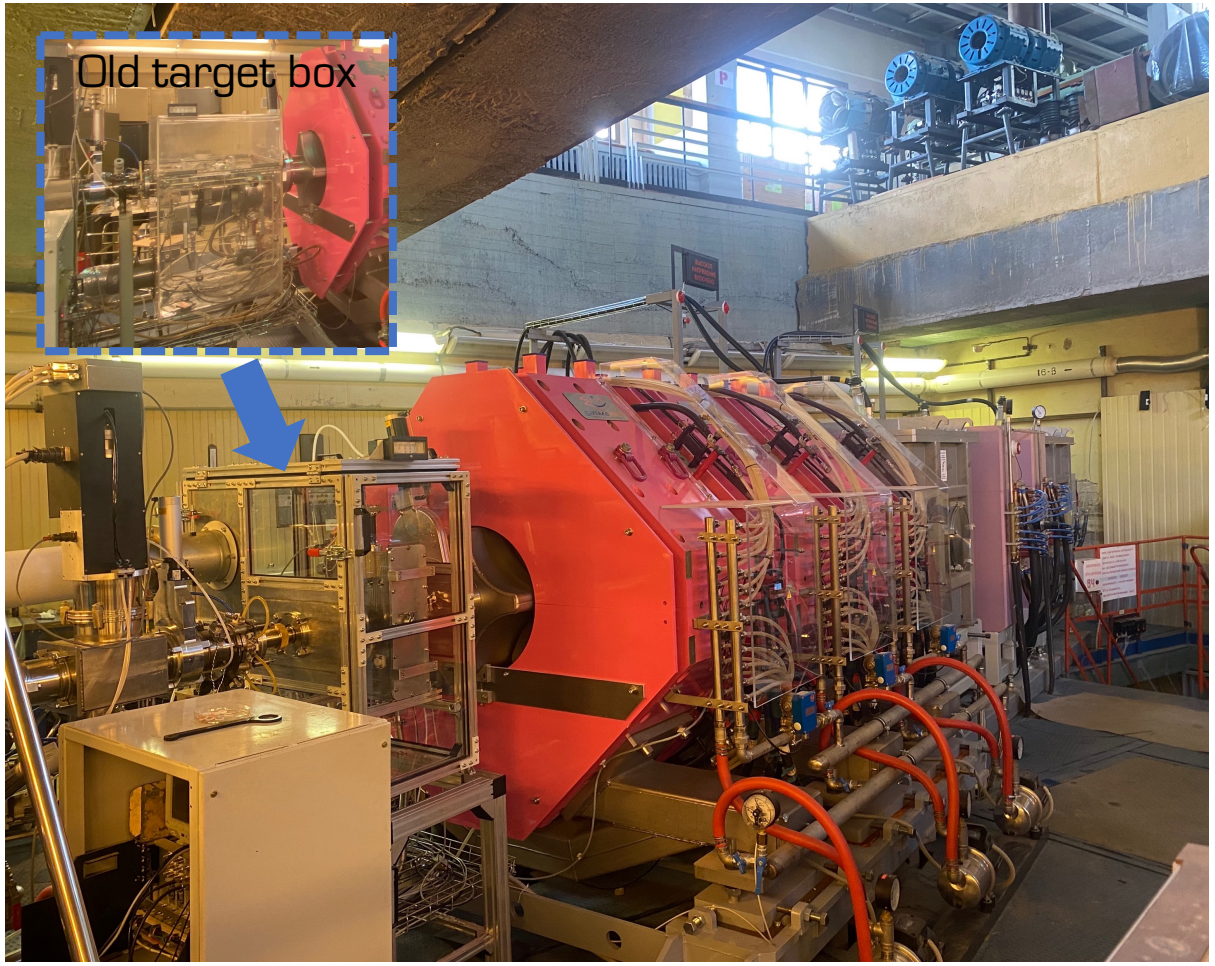


Popeko A. G. et al.
Separator for Heavy ELement Spectroscopy – velocity filter SHELS
NIM B 376 (2016) 140–143

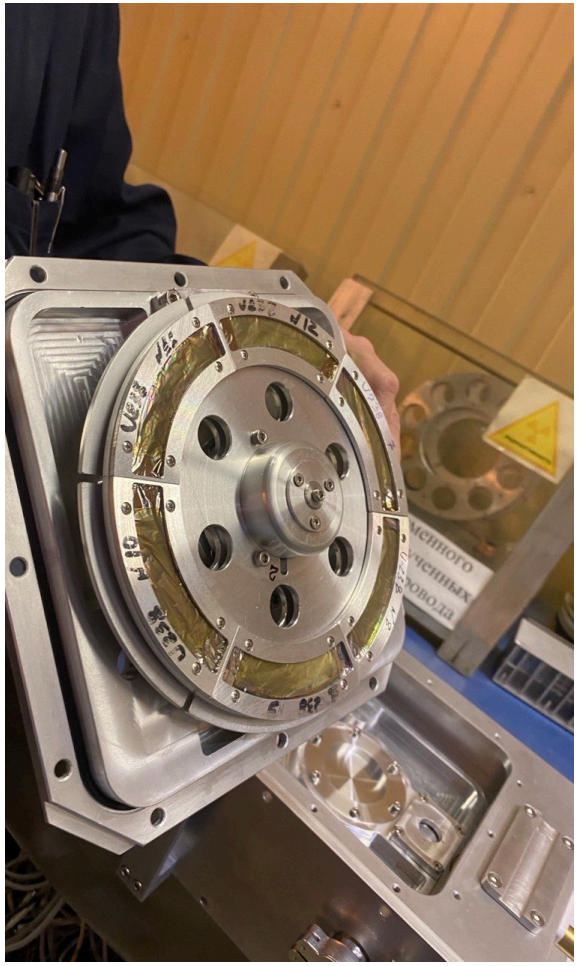
Principal components of SHELS.

Quadrupole lenses	
Maximum field gradient	13 T/m
Effective length	38 cm
Aperture radius	10 cm
Electrostatic deflectors	
Maximum field gradient	40 kV/cm
Effective length	65.7 cm
Distance between plates	10–20 cm
Nominal deflection angle	8°
Magnetic dipoles D22-1,2	
Maximum field strength	0.8 T
Effective length	59.7 cm
Gap height	13.5 cm
Nominal deflection angle	22°
Magnetic dipole D8	
Maximum field strength	0.2 T
Effective length	58.8 cm
Gap height	14 cm
Nominal deflection angle	8°

The New Target Module on SHELS (2025)



New target box



Rotating target
(150 mm diameter wheel)



Stationary targets and C stripping foils

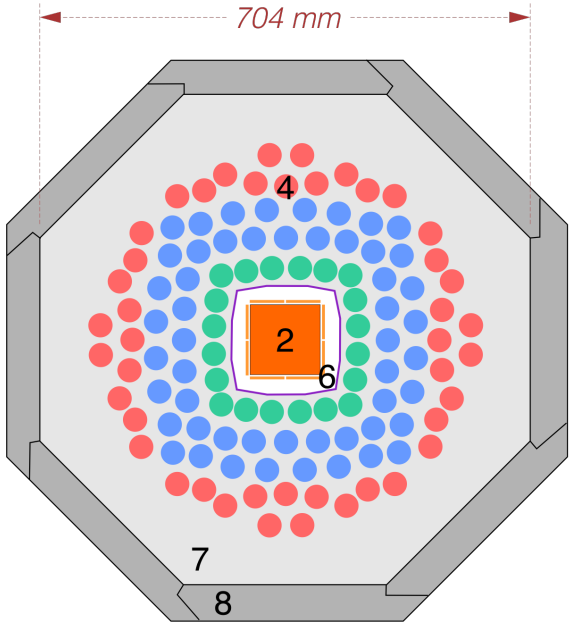
SFiNx – Spontaneous Fission, Neutrons and x-rays

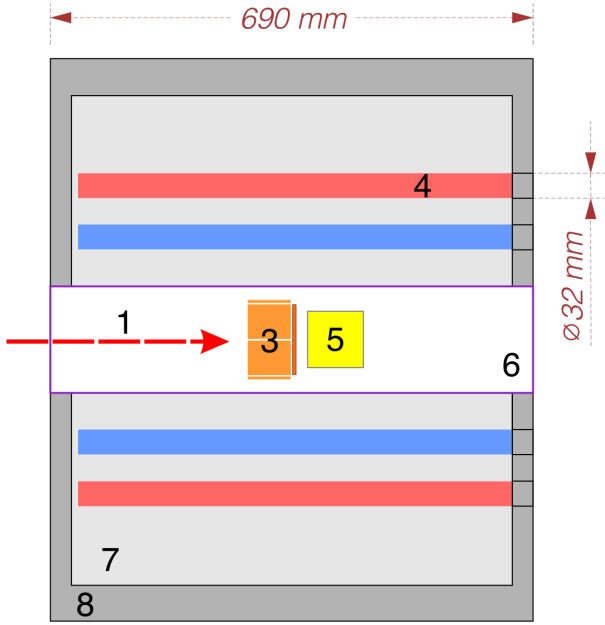




$\varepsilon_n = 56\pm1\%$

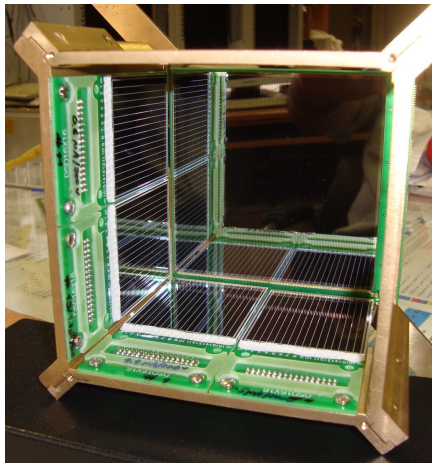
Isaev A. V. et al.
The SFiNx detector system
PEPAN Letters 19 (2022)
P. 37–45





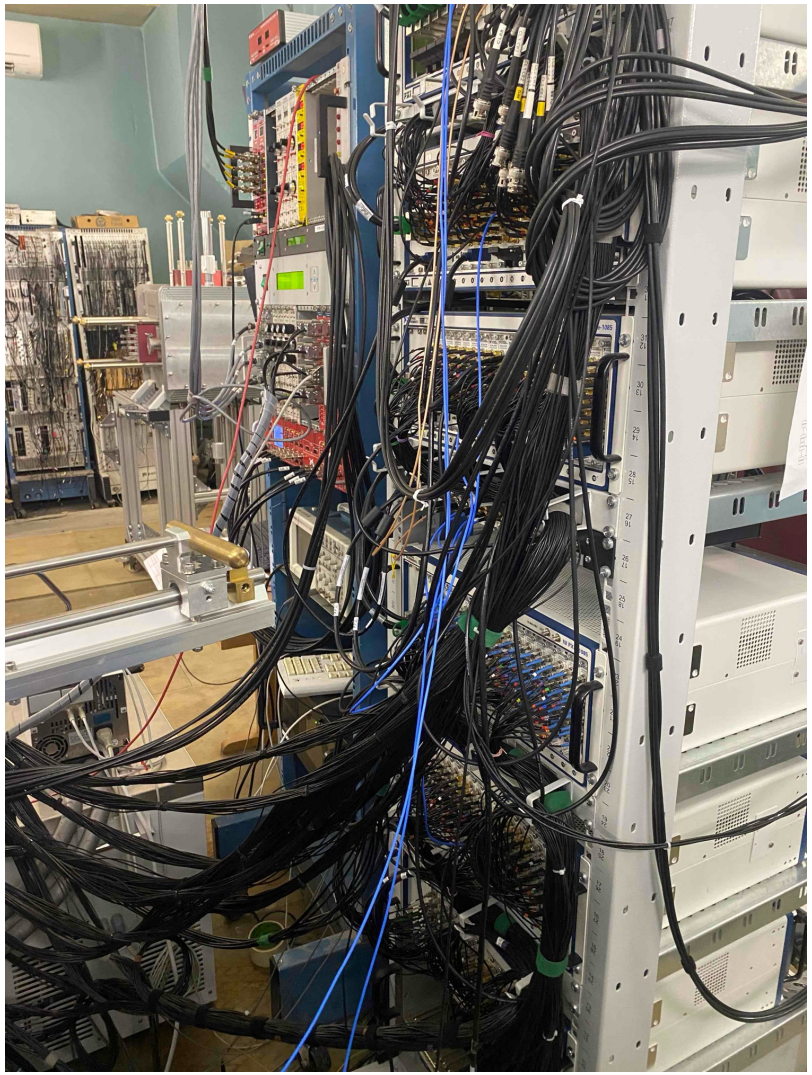
The legend:

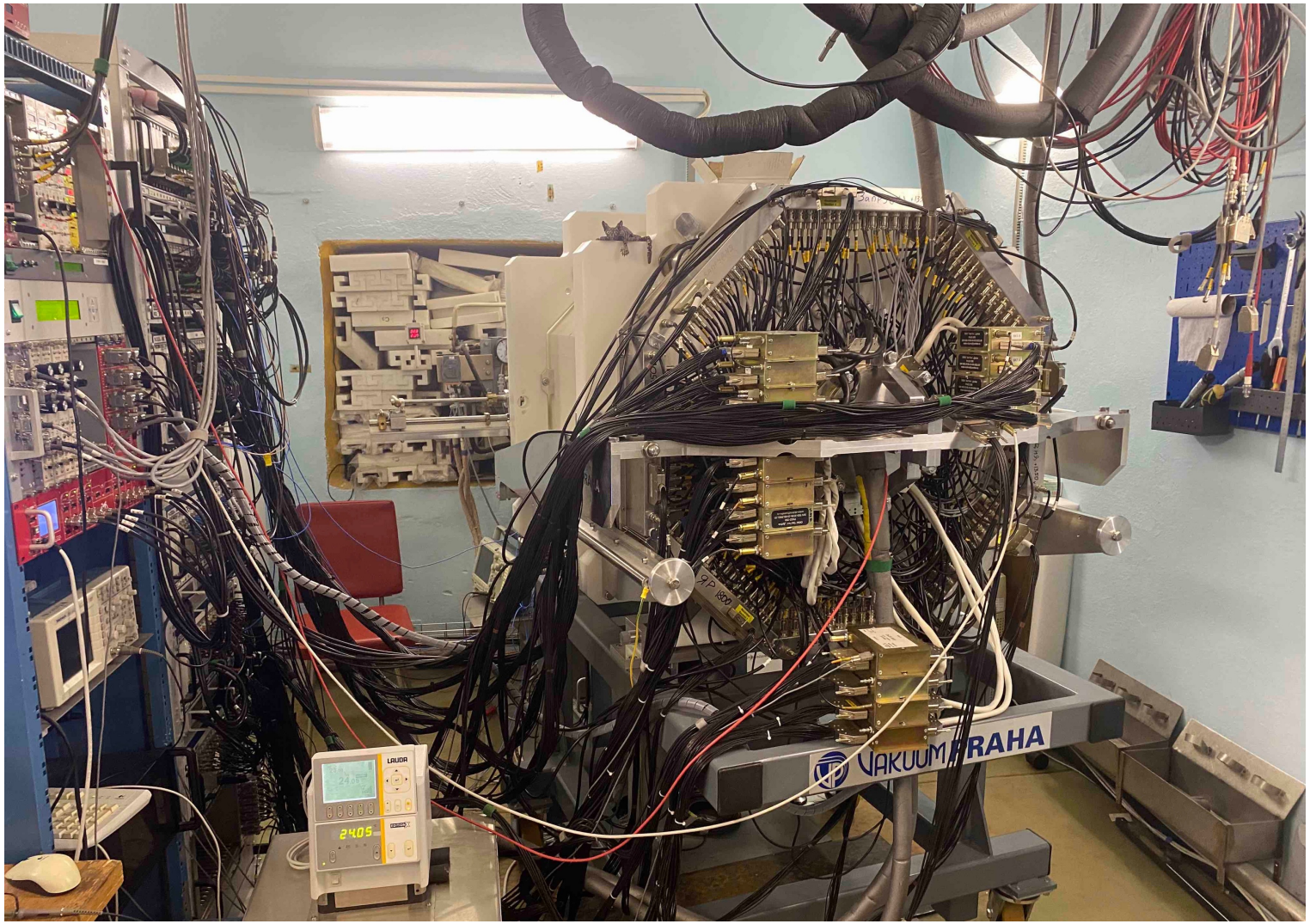
1 – evaporation residues
2 – focal-plane Si-detector
3 – side Si-detectors
4 – ^{3}He-counters
5 – scintillator
6 – vacuum chamber
7 – moderator
8 – shield



DSSD 100×100 mm
128×128-strips

SFiNx – Spontaneous Fission, Neutrons and x-rays





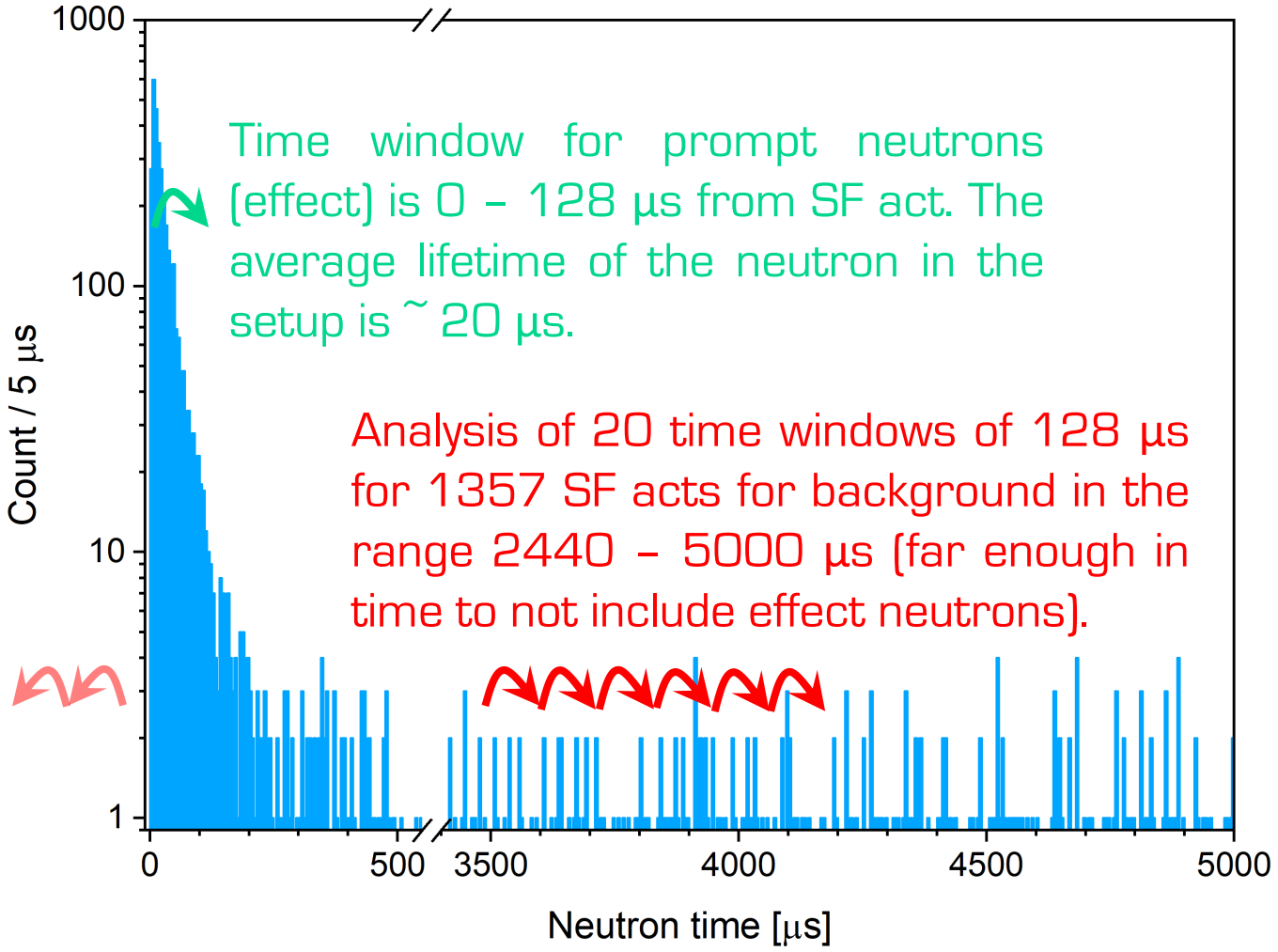
Mukhin R.S. et al.
Digital Signal Processing for the GABRIELA Detector Assembly
Acta Phys. Pol. B Proc. Suppl. 14, 705 (2021)

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

The Background Influence (SHELS)

The background neutron multiplicity distribution was taken to perform the background correction.

SFiNx is always waiting for neutron events!



Distribution of time differences between neutron detection and the SF of ^{250}No.

- The average load of the detector: ~100 n/s (or 0.0128 n/window).
- The average background neutron multiplicity with 27140 windows is 0.015 n/window.

The observed of detecting background neutrons of the given multiplicity f_b, and the restored emission probability ν for the prompt neutrons multiplicity k for ^{250}No.

k	N	f_b	ν
0	32	0.9852	0.009 ± 0.007
1	100	0.0145	0.004 ± 0.006
2	169	2.7×10^{-4}	0.102 ± 0.015
3	125	0	0.226 ± 0.018
4	63	0	0.281 ± 0.019
5	18	0	0.232 ± 0.020
6	3	0	0.120 ± 0.017
7	0	0	0.024 ± 0.013
8	0	0	0.002 ± 0.003
9	0	0	0.001 ± 0.003

R.S. Mukhin, et al. Prompt neutron emission in ^{250}No spontaneous fission associated with ground and isomeric state decays. Chinese Physics C, 2024, 48(6): 064002.

Unfolding of Multiplicity Distribution

- Since the detector efficiency is far from 100%, the measured neutron distribution is highly distorted

- Let's assume that the number of neutrons registered is a random variable that obeys the binomial distribution

$\boldsymbol{n}$ – maximum neutron multiplicity

$\boldsymbol{x} \in \mathbb{R}^{\boldsymbol{1,n}}$ – true neutron multiplicities

$\boldsymbol{K} \in \mathbb{R}^{\boldsymbol{n,n}}$ – detector response matrix:

$$K_{i,j} = \frac{j!}{i!\,(j-i)!}\varepsilon^{i}(1-\varepsilon)^{j-i}$$

where $\boldsymbol{i}$ – is the number of emitted neutrons, $\boldsymbol{j}$ – is the number of measured neutrons, $\boldsymbol{\varepsilon}$ – single neutron registration efficiency.

$\boldsymbol{y} \in \mathbb{R}^{\boldsymbol{1,n}}$ – measured neutron multiplicities:

$$y = Kx$$

$x_d = \left(K^T K\right)^{-1} K y$ – direct solution of the problem

A direct solution often doesn't make sense, when the noise level is high (including statistical uncertainties)!

Tikhonov Statistical Regularization

- The essence of the method is to **find an approximate solution using a priori information** about the distribution:
  - Smooth
  - Flat on the "tails"
  - Has no negative values
- The regularization matrix ***R*** has the form:

$$R = \begin{pmatrix} -1 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 1 & -2 & 1 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & -3 & 2 \end{pmatrix} \in \mathbb{R}^{(n-1)\times n}$$

- Regularized solution:

$$\boldsymbol{x_r = \left(L^T L + \alpha s^2 R^T R\right)^{-1} L^T g}$$

- $L \sim K, g \sim y,$
- $s = \sqrt[n]{\prod_0^n s_i}$; where s_i are the uncertainties of the measured distribution
- α – regularization parameter (smoothing degree)
- $\boldsymbol{\sigma^2} = s^2 diag((L^T L + \alpha s^2 R^T R)^{-1})$ – uncertainties of the regularized solution

Mukhin R.S. et al. Reconstruction of Spontaneous Fission Neutron Multiplicity Distribution Spectra by the Statistical Regularization Method. Phys. Part. Nuclei Lett. 18, 439–444 (2021).
Mukhin R.S. et al. Prompt neutron multiplicity from spontaneous fission of ^{244}Fm. Eur. Phys. J. A 60, 223 (2024).
Mukhin R.S. et al. Analysis of the shape of multiplicity distributions of prompt neutrons emitted in spontaneous fission. J Radioanal Nucl Chem 333, 1559–1564 (2024).

Direct Solution vs Tikhonov Regularization

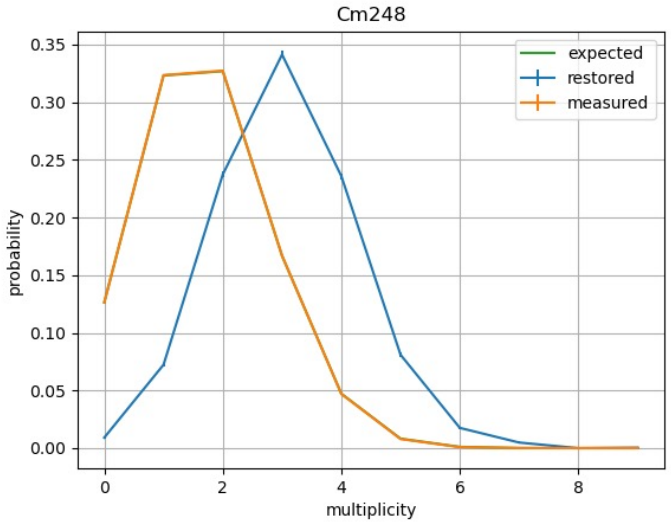
$\varepsilon \sim 55\%$

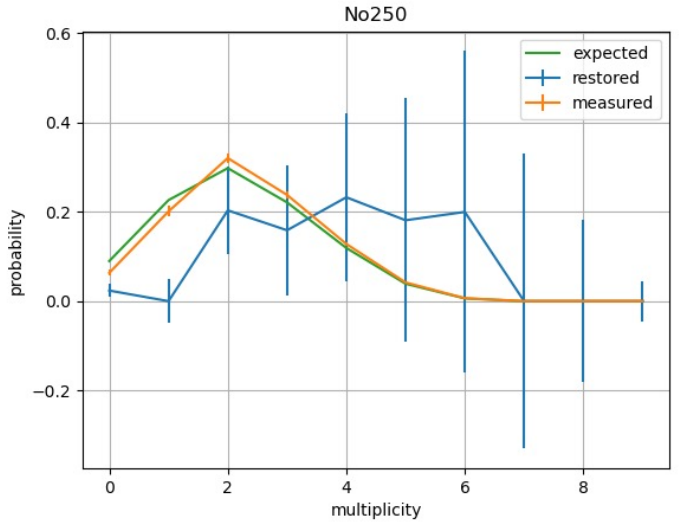
Direct Solution

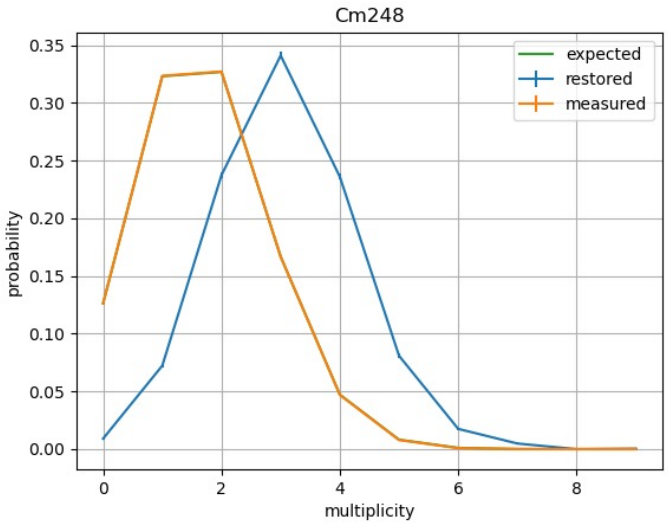
Regularization
($\alpha = 89$)

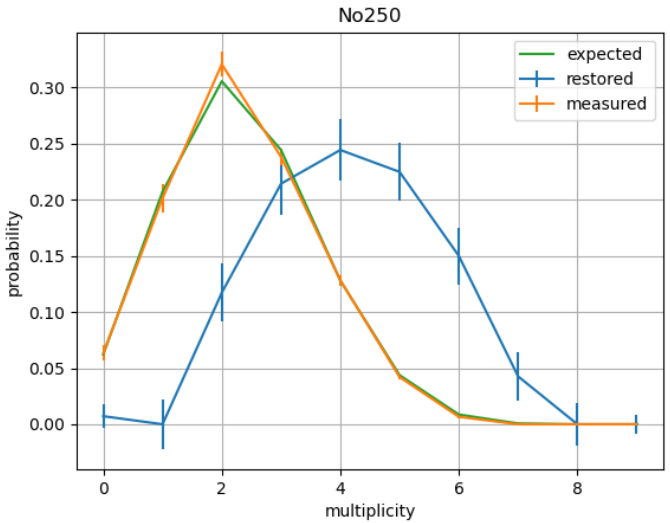
850k ^{248}Cm SF

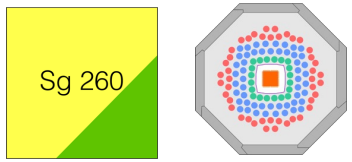
1357 ^{250}No SF





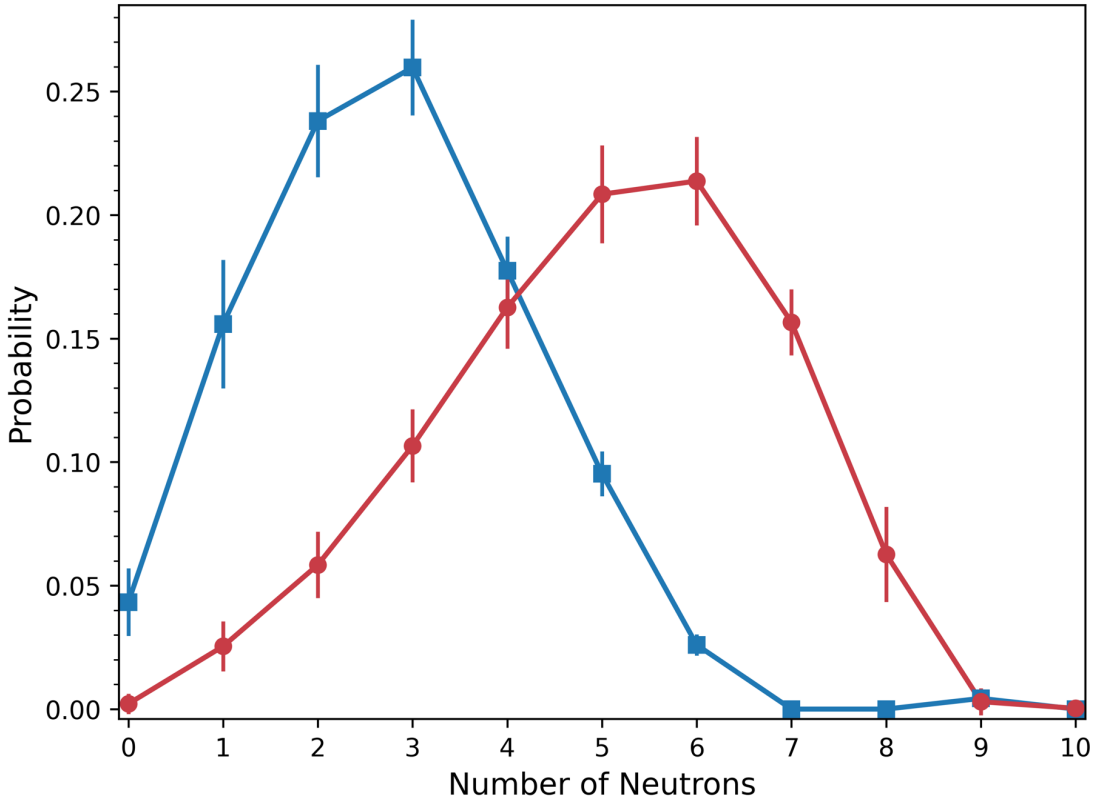






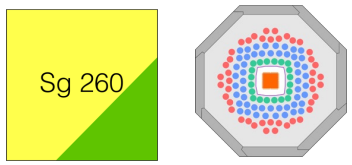
Isotope ^{260}Sg

Reaction	^{207}Pb + ^{54}Cr
Targets PbS	345 and 455 μg/cm^2 1.5 μm Ti; ^{207}Pb > 99%
$E_{1/2}$, MeV	249 – 255
ε_n, %	55.5±1
$\sum_{SF}$	**231**
$\sum_n$	**645**
$\bar{\nu}$	5.03±0.14
P_n	received for the first time
$T_{1/2}$, ms	~7
b_{SF}	~0.3

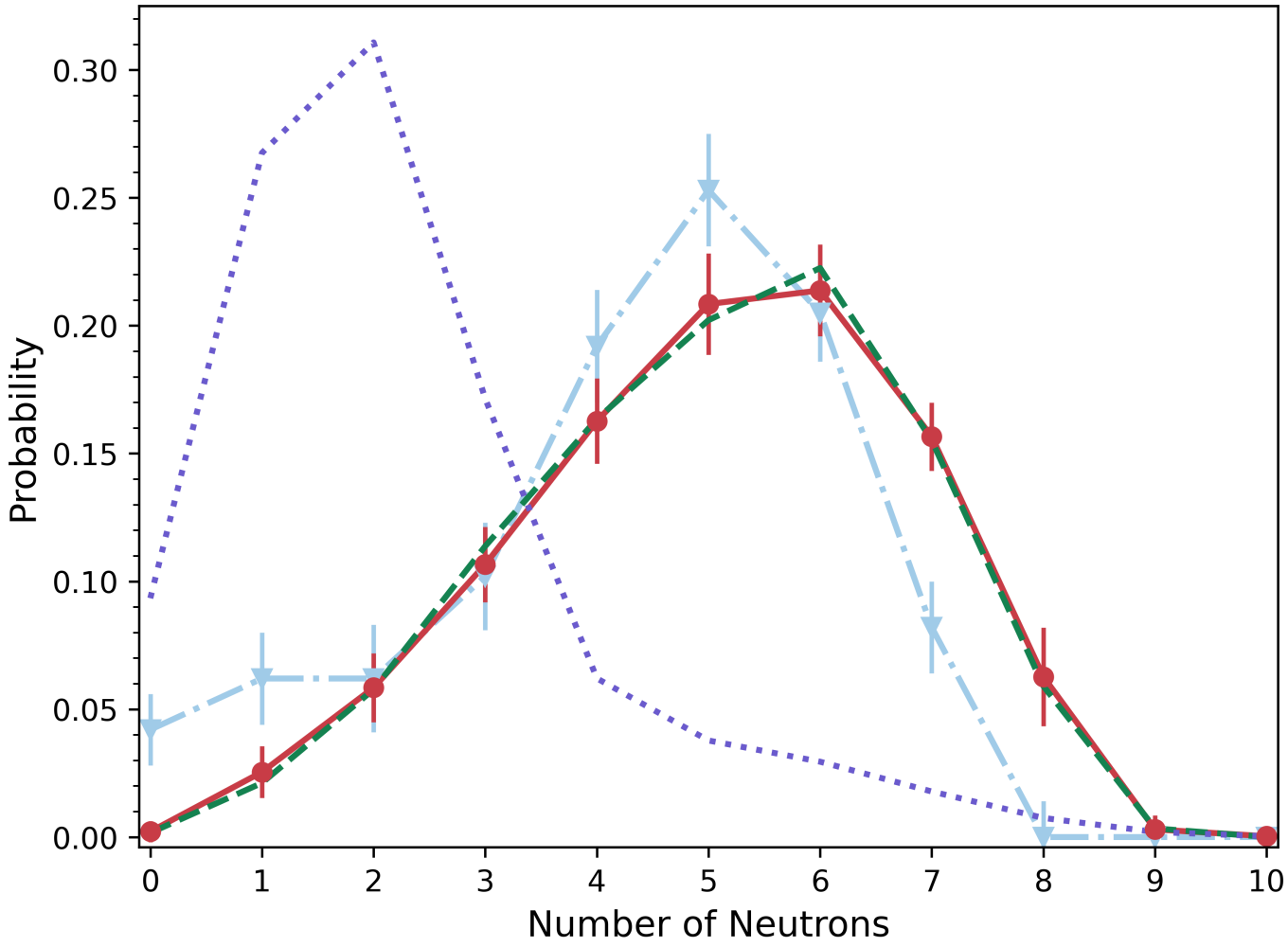


Neutron multiplicity distributions for SF of ^{260}Sg: measured distribution (blue squares) and reconstructed distribution (red circles).

Isaev A. V. et al.
Prompt neutron emission in the spontaneous fission of ^{258,260}Sg
JINR Preprint E7-2026-3



Isotope ^{260}Sg



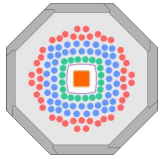
Prompt neutron emission probability distributions for ^{260}Sg: the **experimental distribution** obtained in this work and theoretical predictions from the **scission-point model with a random walk** and **GEF model**. For comparison, the prompt neutron **multiplicity distribution of ^{256}Rf** is also included.

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

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

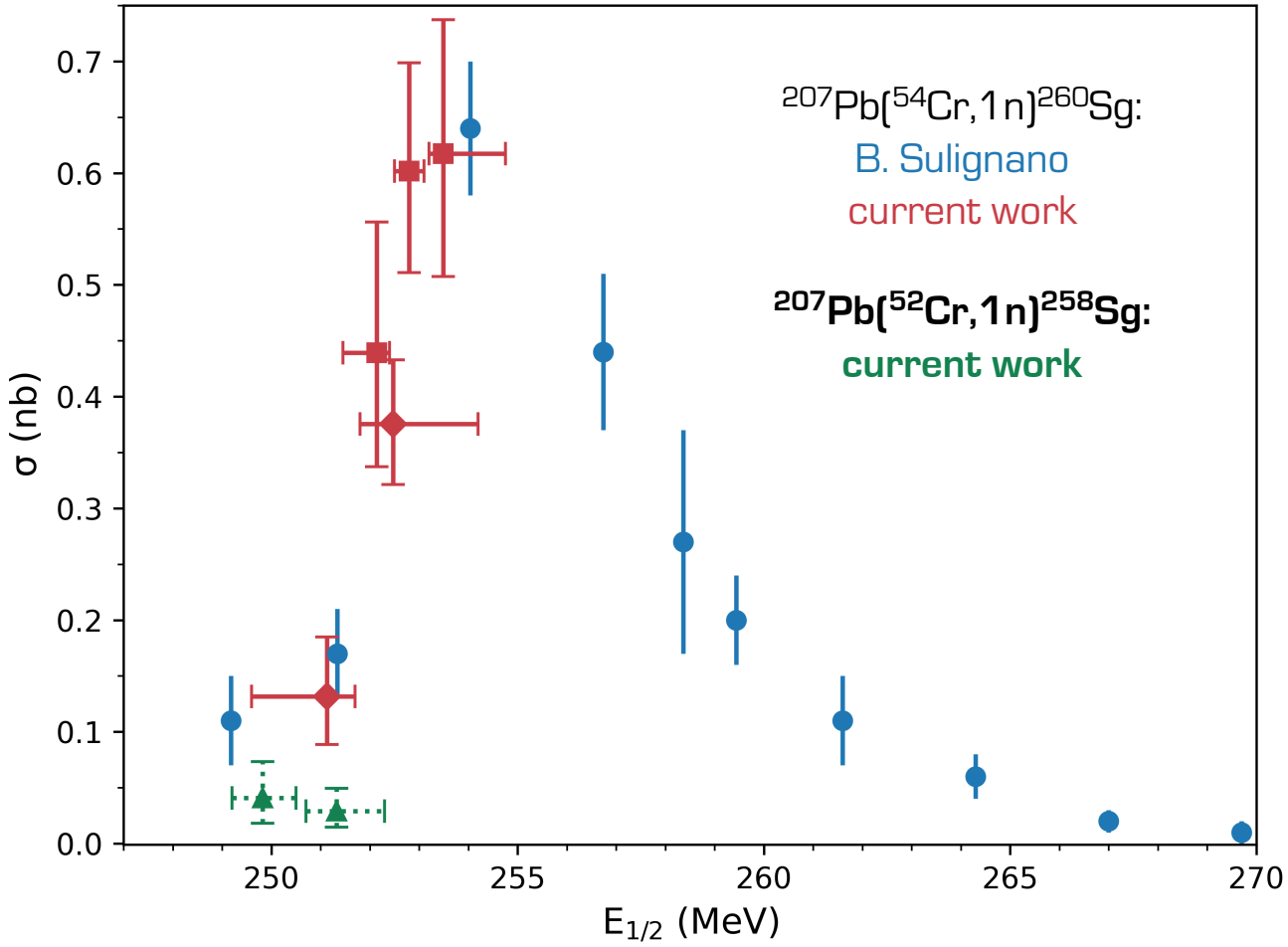
Isaev A. V. et al.
Prompt neutron emission in the spontaneous fission of ^{258,260}Sg
JINR Preprint E7-2026-3; Submitted to PRC

Sg 258



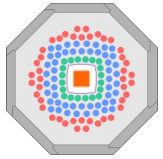
Isotope ^{258}Sg

Reaction	^{207}Pb + ^{52}Cr
Target PbS	455 μg/cm^2 1.5 μm Ti; ^{207}Pb > 99%
$E_{1/2}$, MeV	249 – 253
ε_n, %	56.8±1
$\sum_{SF}$	**9**
$\sum_n$	**25**
$\bar{\nu}$	4.9±0.4
P_n	received for the first time
$T_{1/2}$, ms	~2.2
b_{SF}	~1



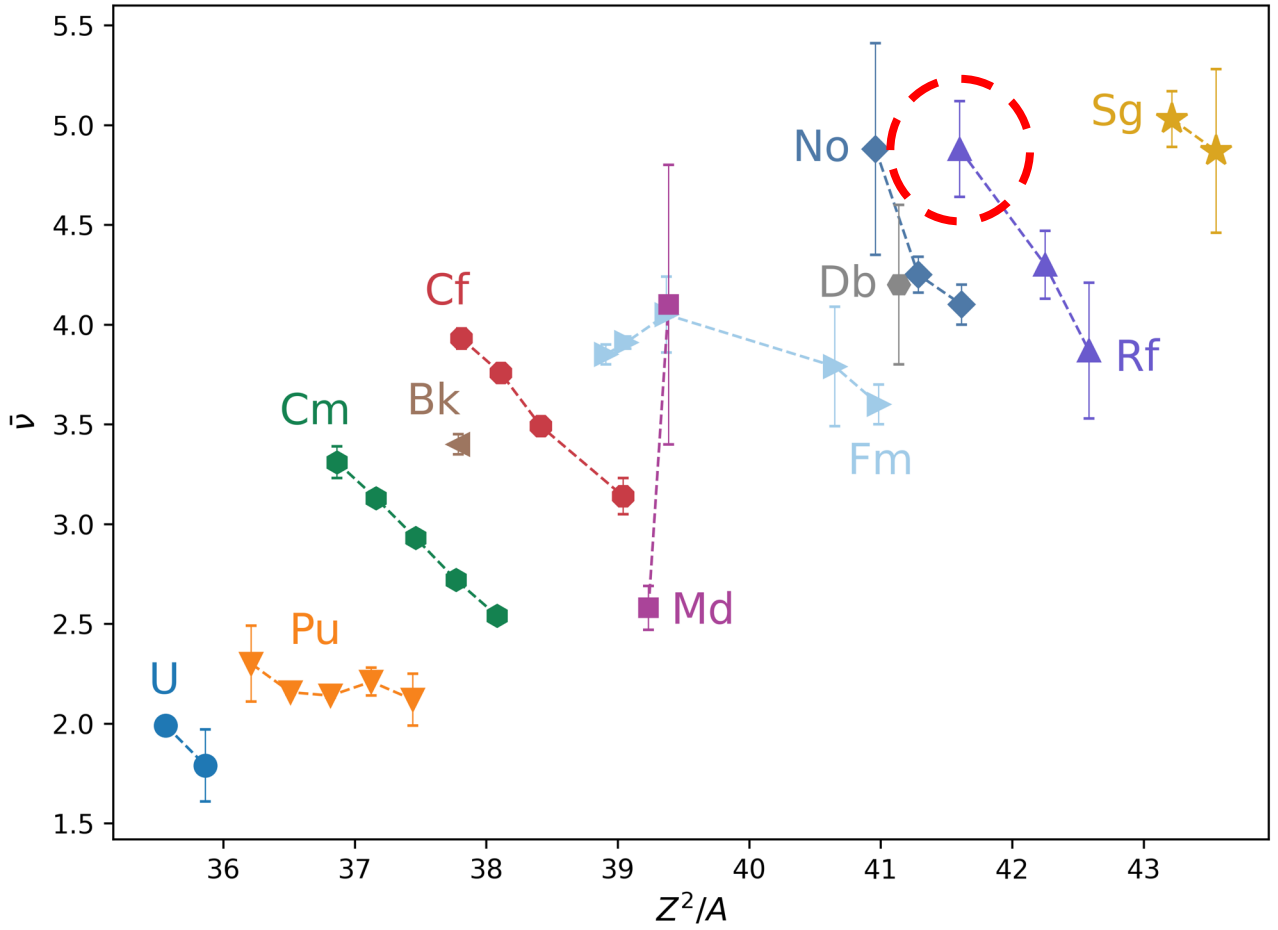
Isaev A. V. et al.
Prompt neutron emission in the spontaneous fission of ^{258,260}Sg
JINR Preprint E7-2026-3

Rf 260



Isotope ^{260}Rf

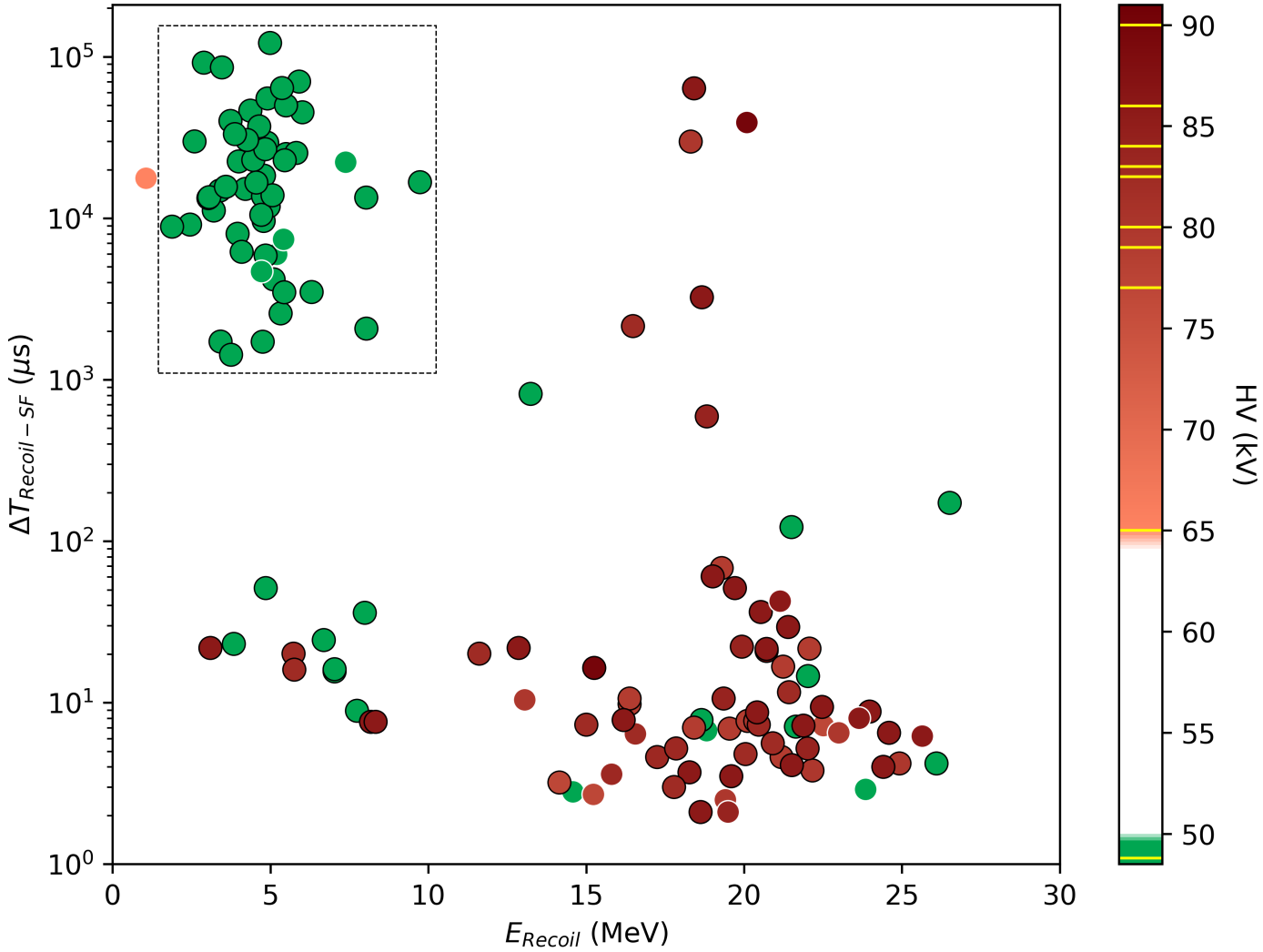
Reaction	$^{238}U + ^{26}Mg$
Target U_3O_8	287 μg/cm^2 1.5 μm Ti
$E_{1/2}$, MeV	128 – 134.5
σ_{max}, nb	~0.2
ε_n, %	56.8±1
$\sum_{SF}$	**53**
$\sum_n$	**147**
$\bar{\nu}$	4.88±0.24
P_n	received for the first time
$T_{1/2}$, ms	~17



Isaev A. V. et al.
Average number of prompt neutrons in the spontaneous fission of ^{260}Rf
JINR Preprint E7-2026-18; Submitted to EPJ A

Rf 260

Isotope ^{260}Rf



Distribution of time differences between recoil implantation and fission-fragment detection as a function of recoil energy.

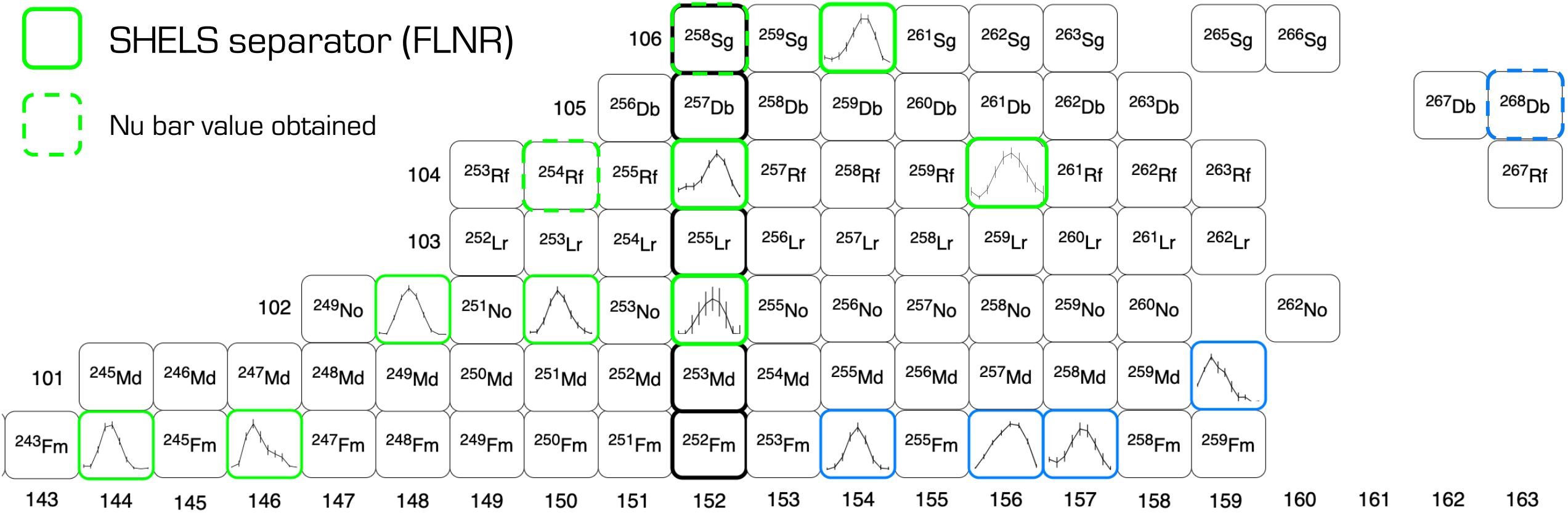
Green markers indicate events found in the complete fusion velocity mode of the SHELS separator (HV = ±49 kV).

Red markers represent events corresponding to the transfer-product velocity regime (HV = ±65 to ±90 kV).

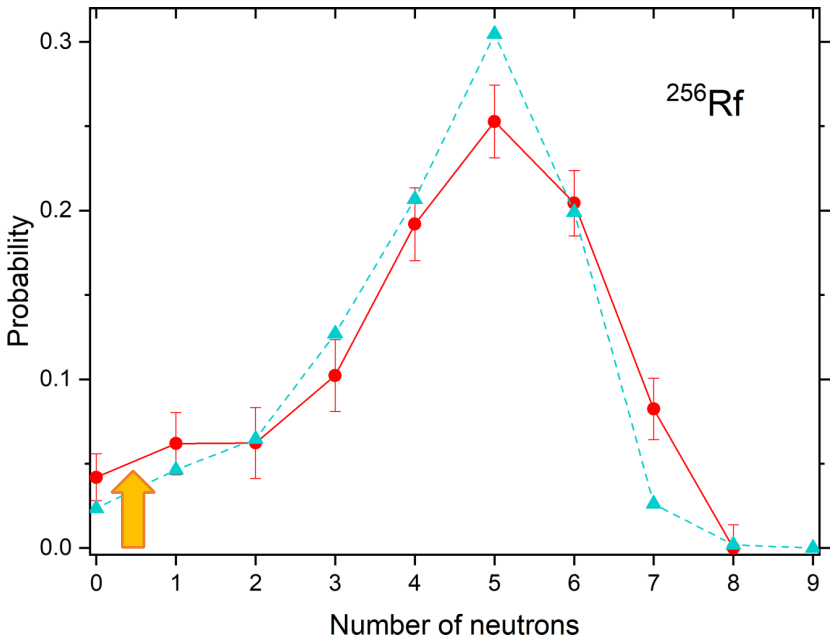
Dashed box indicates the complete fusion cluster of ^{260}Rf.

Isaev A. V. et al.
Average number of prompt neutrons in the spontaneous fission of ^{260}Rf
JINR Preprint E7-2026-18; Submitted to EPJ A

Shapes of the Prompt Neutron Multiplicity Distributions



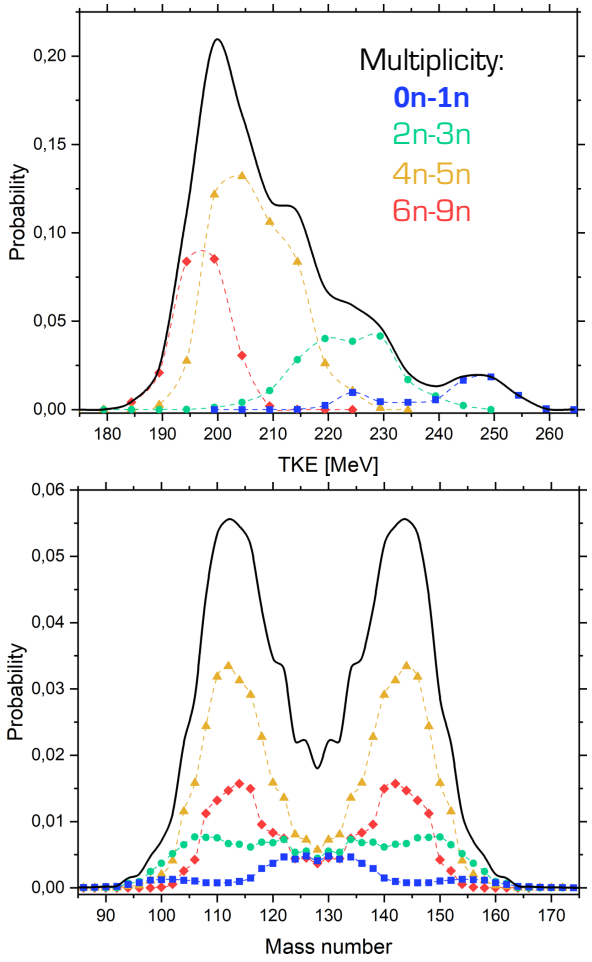
Features of the Prompt Neutron Multiplicity



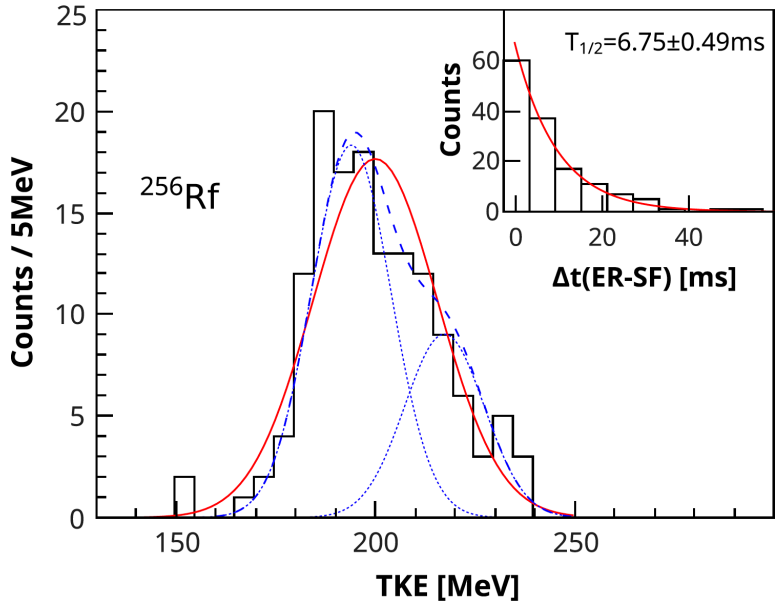
- FLNR, experiment (4.30±0.09)
- ▲ BLTP, ISP model (4.3)

Isaev, A. V. et al.,
Structure of the prompt neutron multiplicity distribution in the spontaneous fission of ^{256}Rf.
Physics Letters B 843 (2023) 138008

ISP model

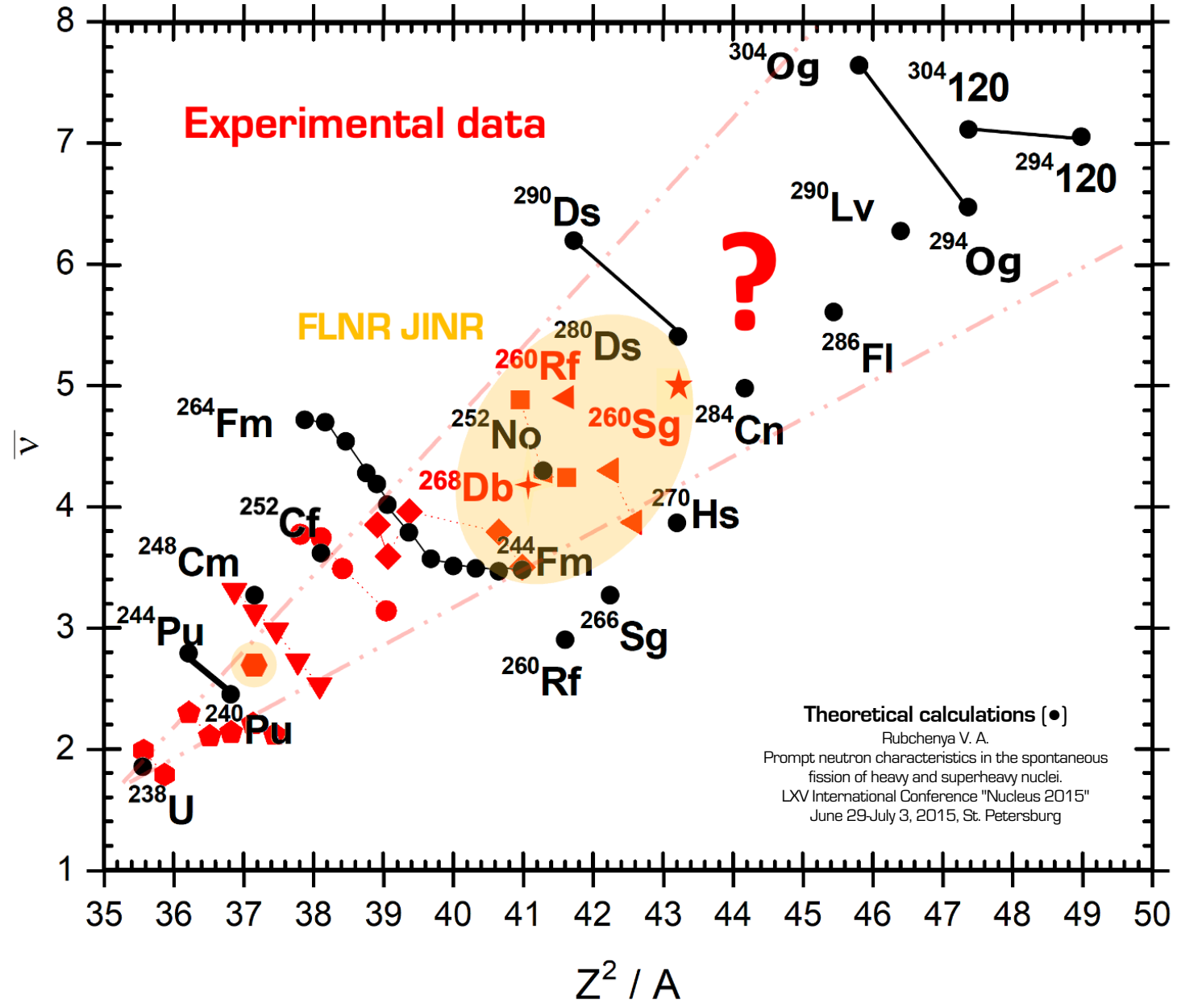


Experiment

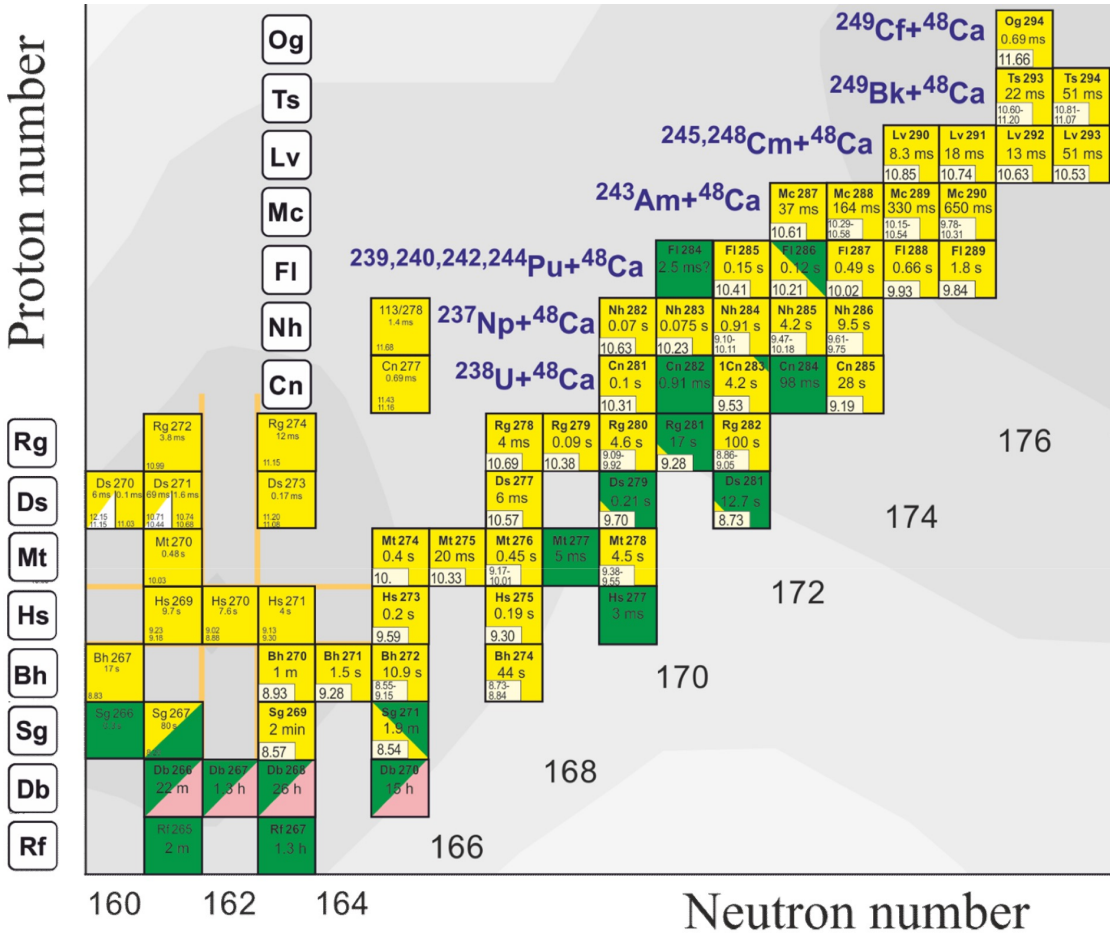


Mosat P. et al.
K isomerism in ^{255}Rf and total kinetic energy measurements for spontaneous fission of ^{255,256,258}Rf
Phys. Rev. C 101 (2020) 034310

Nu-bar Value Systematics



Spontaneous Fission of SHE



Map taken from A.V. Karpov presentation (FLNR)

GRAND separator

- **Year: 2025**
- **Reactions:**

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

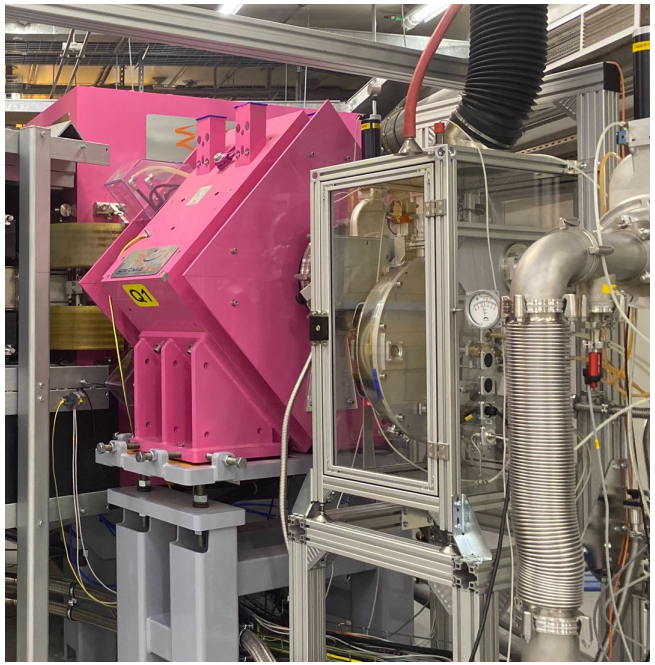
- PuO_2 target:

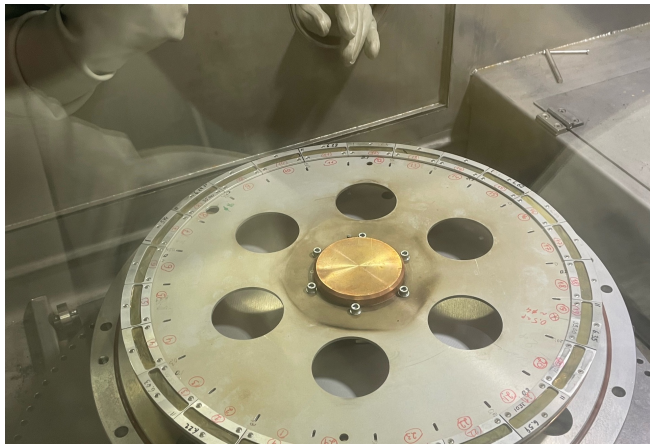
697±50 μg/cm^2 on 1.5 μm Ti backing

- Wheel diameter:

480 mm

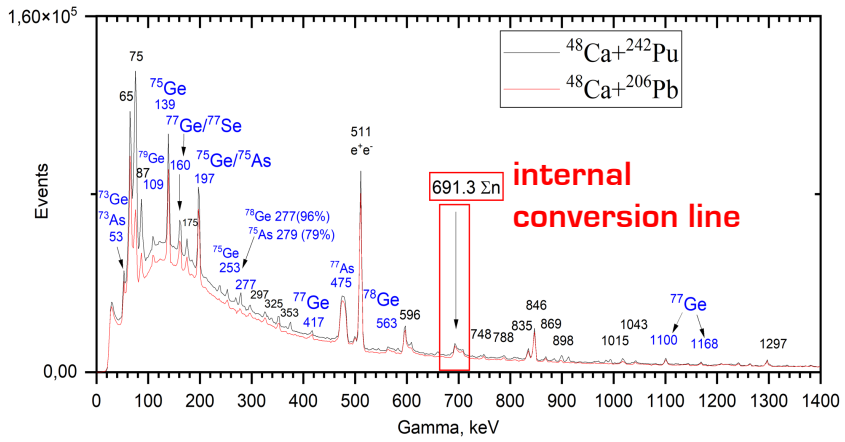
- Total area: 141 cm^2
- Segments: 24
- **Beam: 5 pμA**
- Gas on separator: He



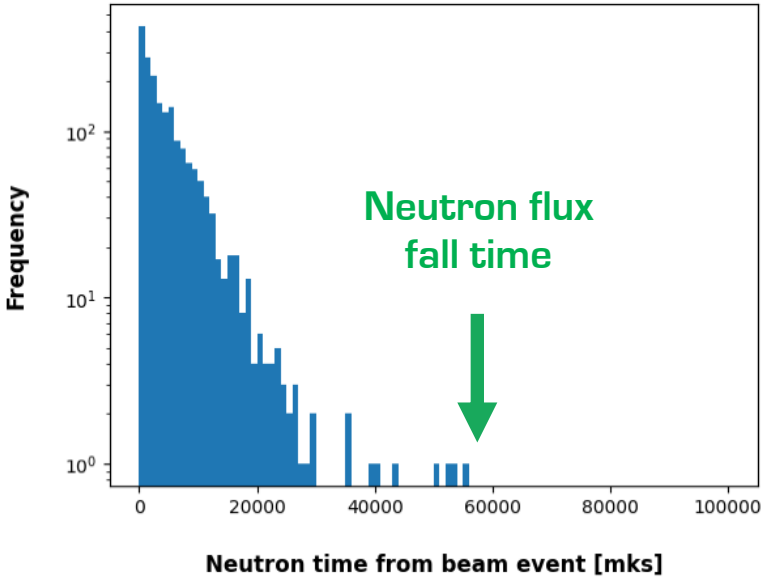


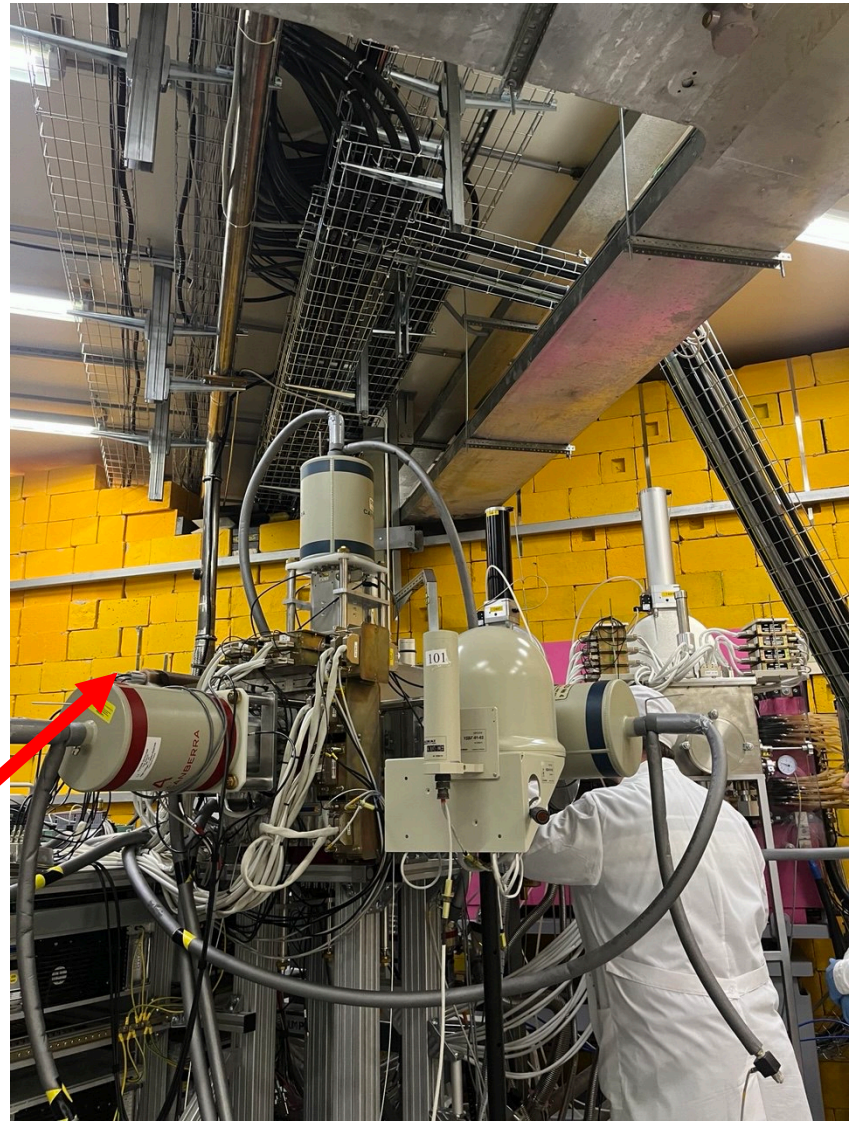
Neutron and Gamma Backgrounds (SHE Factory)

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

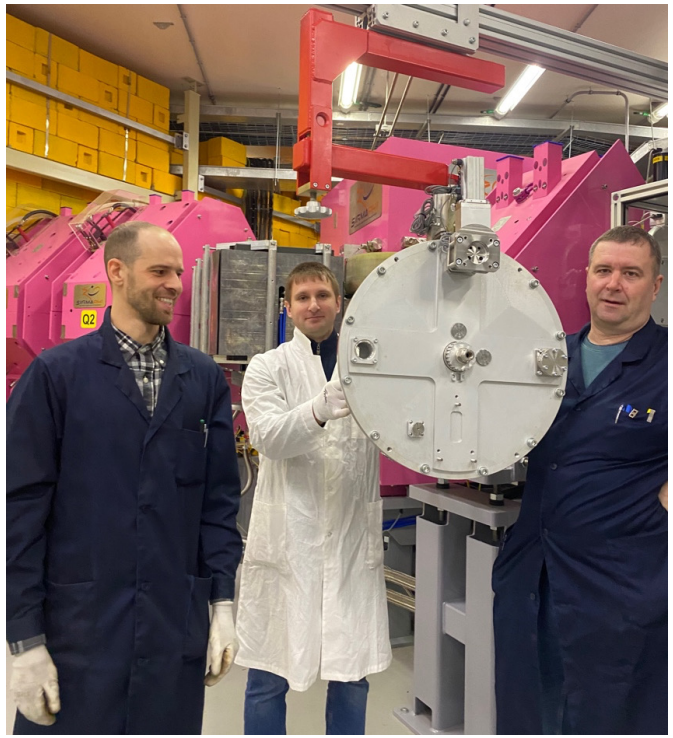
4 pμA of ^{48}Ca

(~7 kHz per counter)

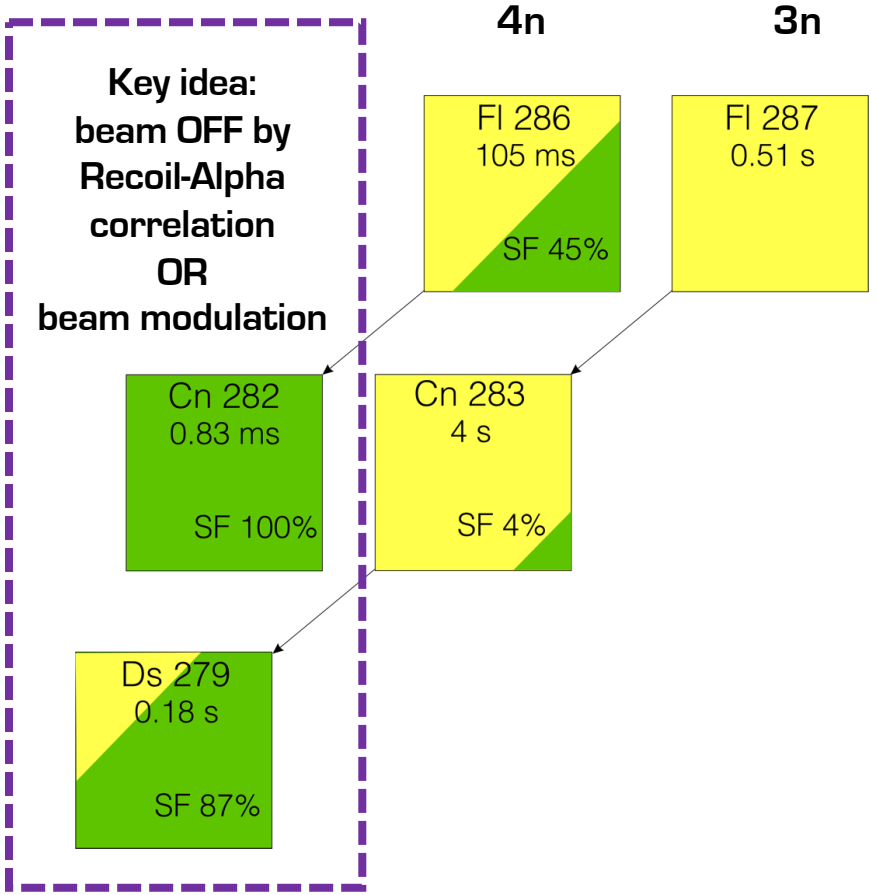


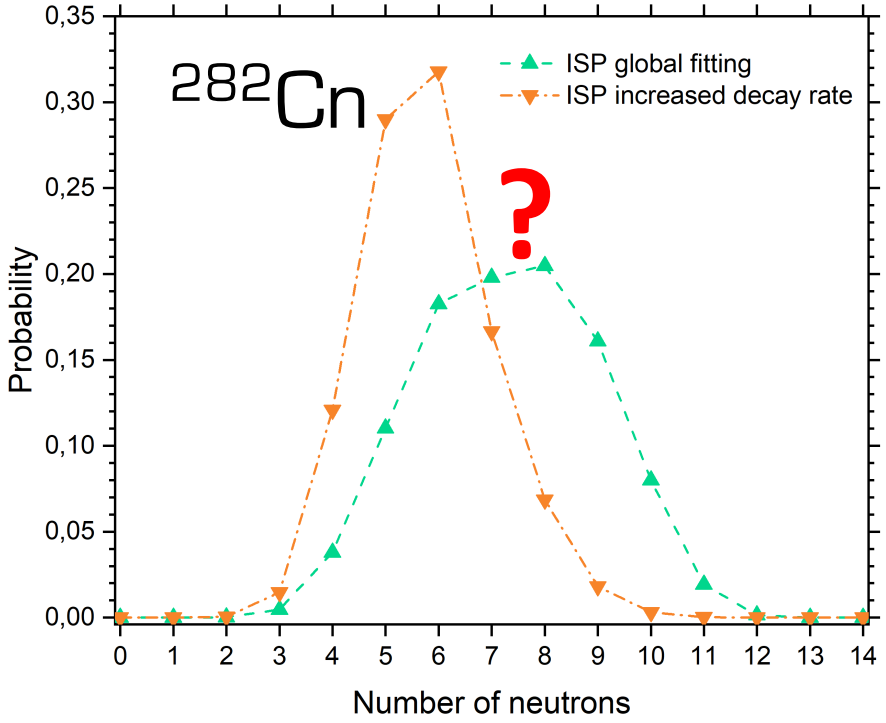
Spontaneous Fission of SHE with SFiNx

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



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





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

- How much statistics is needed?

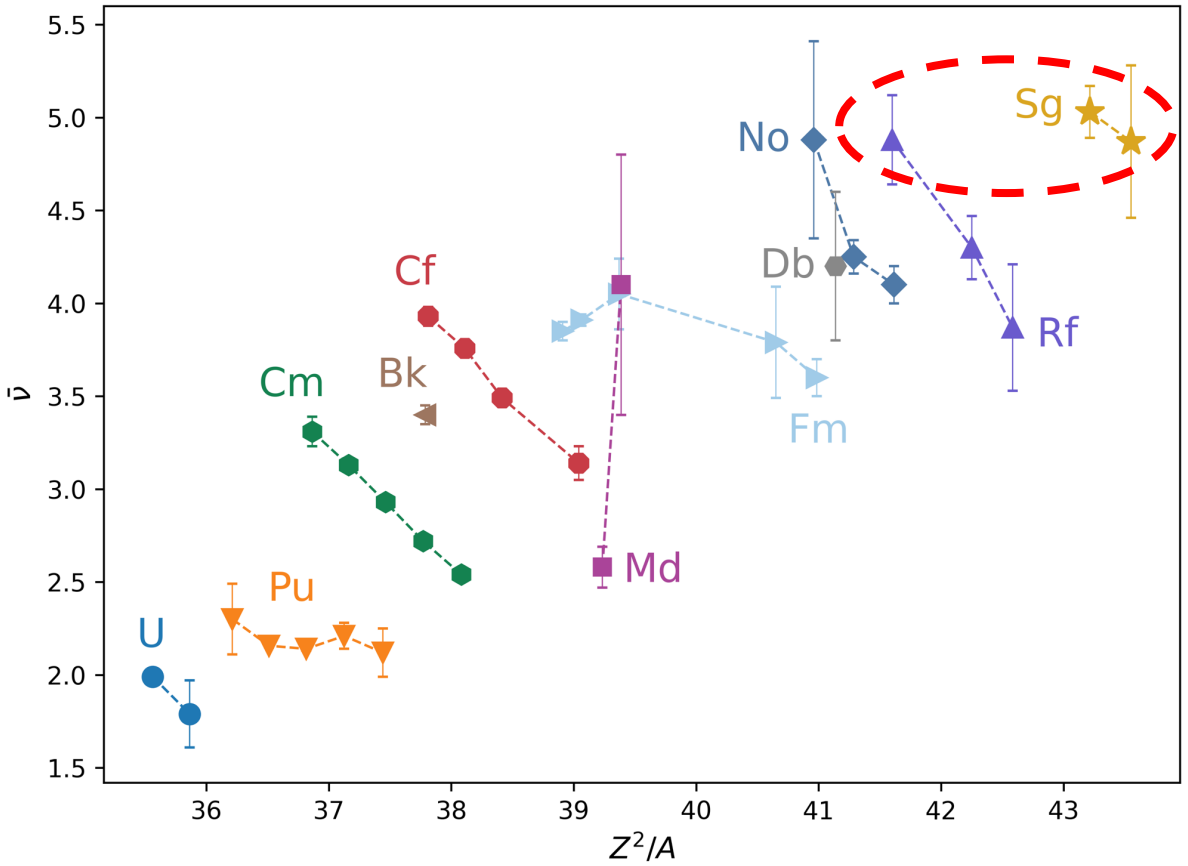
100+ SF for neutron multiplicity

10+ SF for the average number of neutrons

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

Conclusion

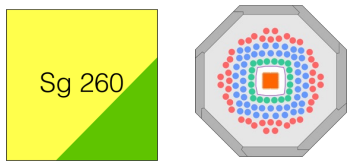
- New data about prompt neutron emission were obtained for a few SHE isotopes:



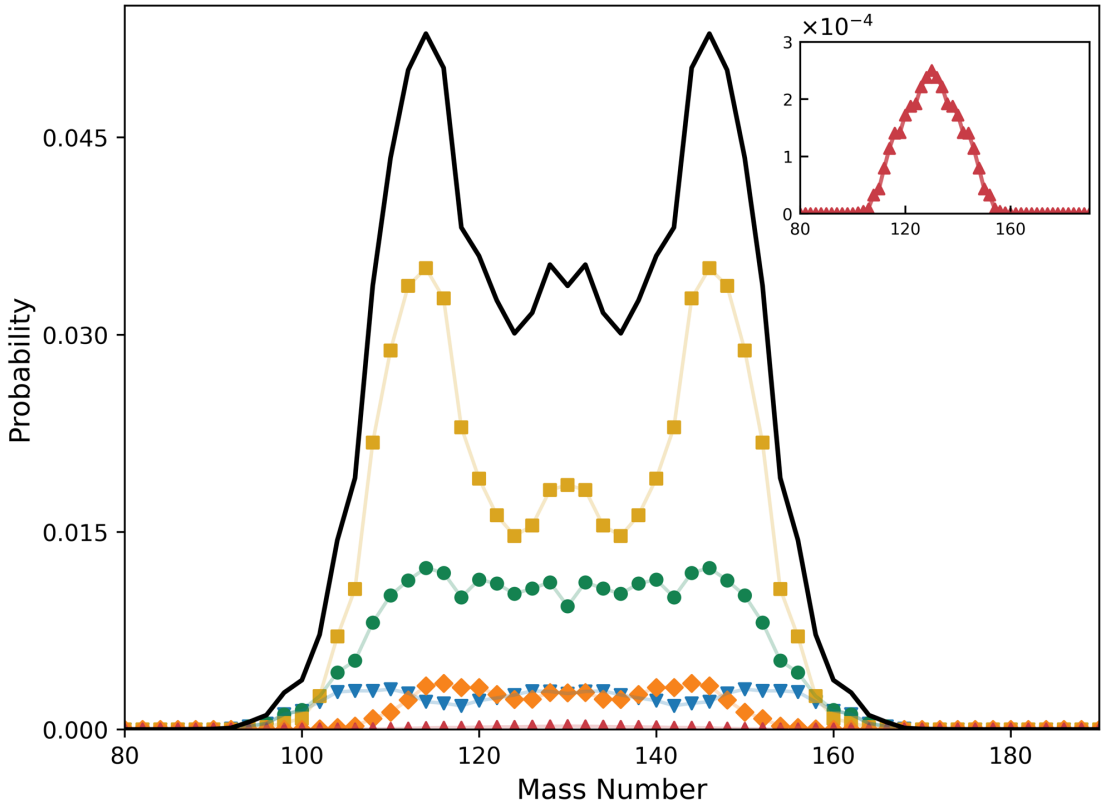
- The highly efficient detection system SFiNx will make it possible to advance research into the region of superheavy elements.

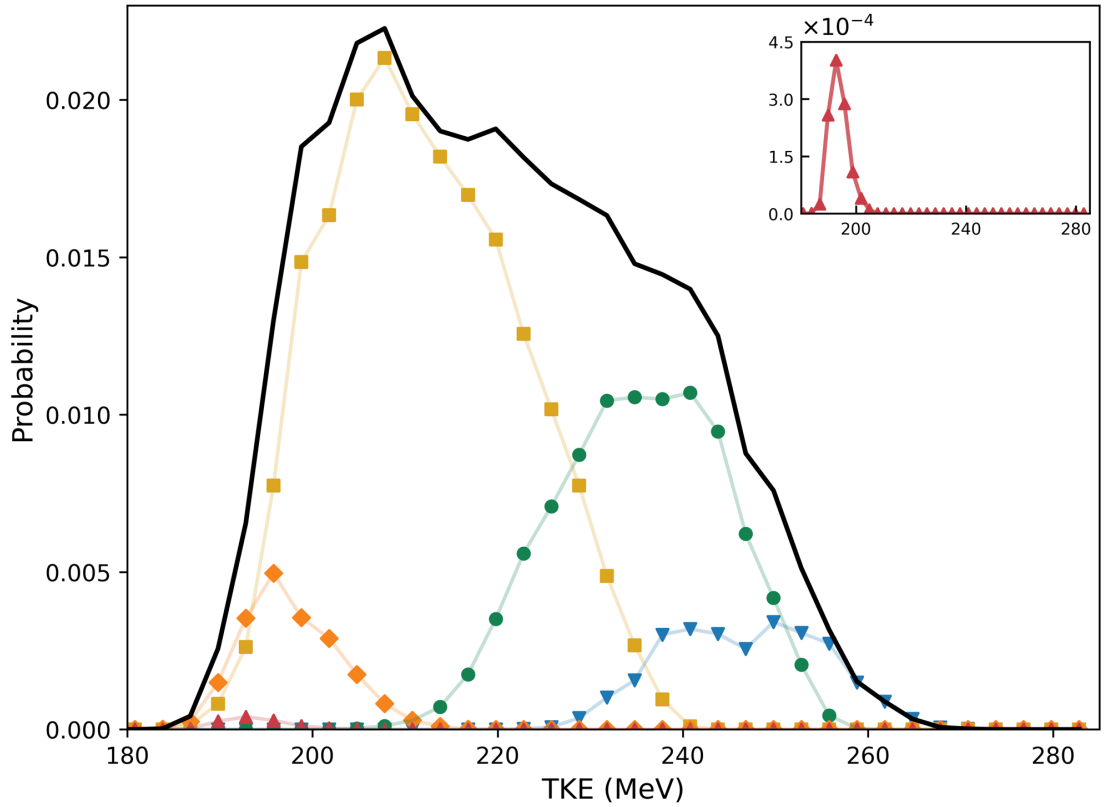


Thank you for your attention!



Isotope ^{260}Sg





Calculated mass distributions of fission fragments (left) and total kinetic energy (TKE) distributions of the fragments (right) for ^{260}Sg spontaneous fission. The results are categorized by prompt neutron multiplicity (ν): the solid black line represents the total distribution summed over all multiplicities; blue triangle down denote $0 \le \nu \le 2$; green circles $3 \le \nu \le 4$; yellow squares $5 \le \nu \le 7$; orange diamonds $\nu = 8$ and red triangle up $9 \le \nu \le 10$ (see inset).

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

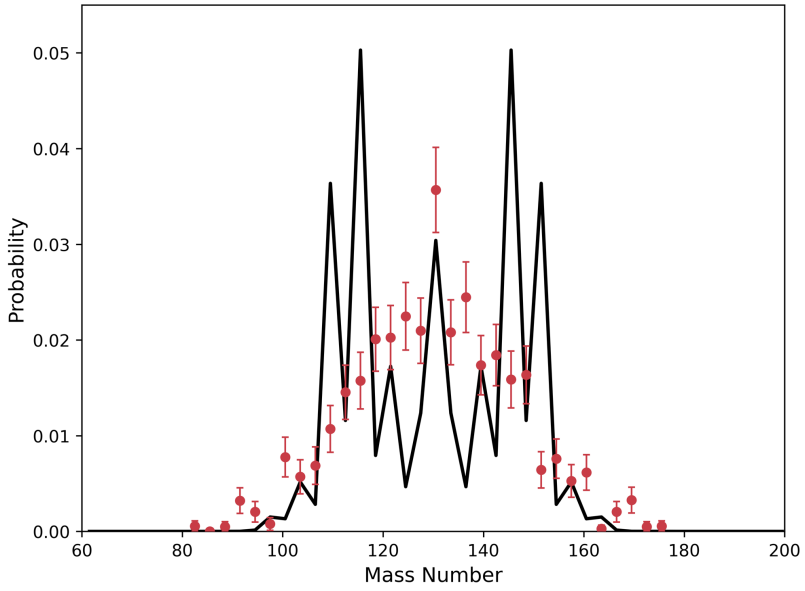
A. V. Andreev, T. M. Shneidman and A. Rahmatinejad

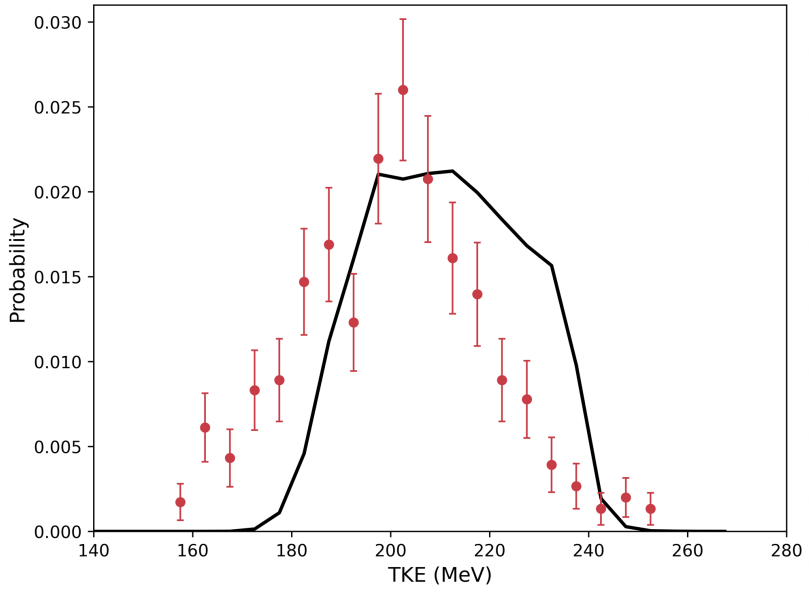
Isaev A. V. et al.
Prompt neutron emission in the spontaneous fission of ^{258,260}Sg
JINR Preprint E7-2026-3; Submitted to PRC

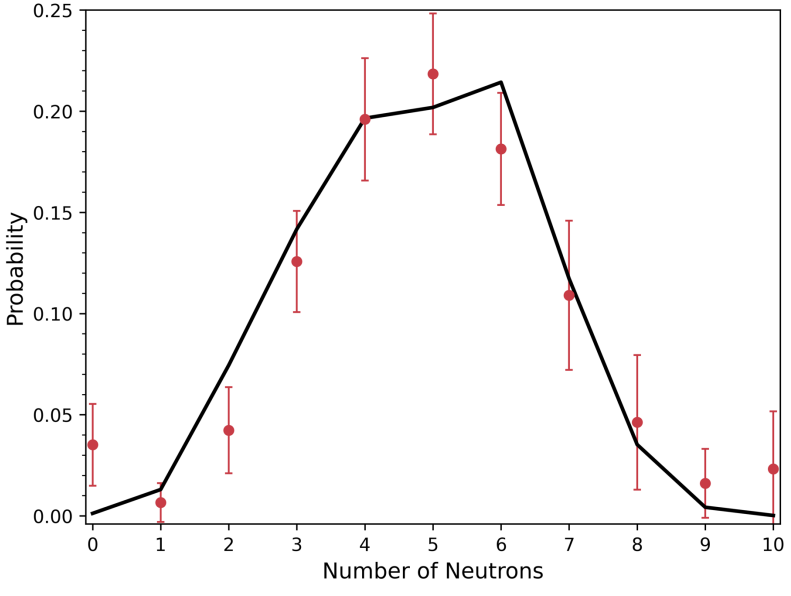
Rf 260

Isotope ^{260}Rf

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







Calculated mass distributions of fission fragments (left), TKE distributions of the fragments (centre), and prompt neutron multiplicity distribution (right) for the spontaneous fission of ^{260}Rf (black solid lines) obtained within the improved scission-point model. Experimental data for fragment masses and TKE (red circles with statistical error bars) are taken from Ref. **[Hulet E.K. et al. PRC 40, 770–784, 1989]** and correspond to post-neutron fragment quantities reconstructed using the 2E method. The experimental prompt neutron emission probability distribution for ^{260}Rf obtained in the **present work** is also shown (red circles).

Isaev A. V. et al.
Average number of prompt neutrons in the spontaneous fission of ^{260}Rf
JINR Preprint E7-2026-18; Submitted to EPJ A