Flerov Laboratory of Nuclear Reactions, JINR

The SFiNx Detector System

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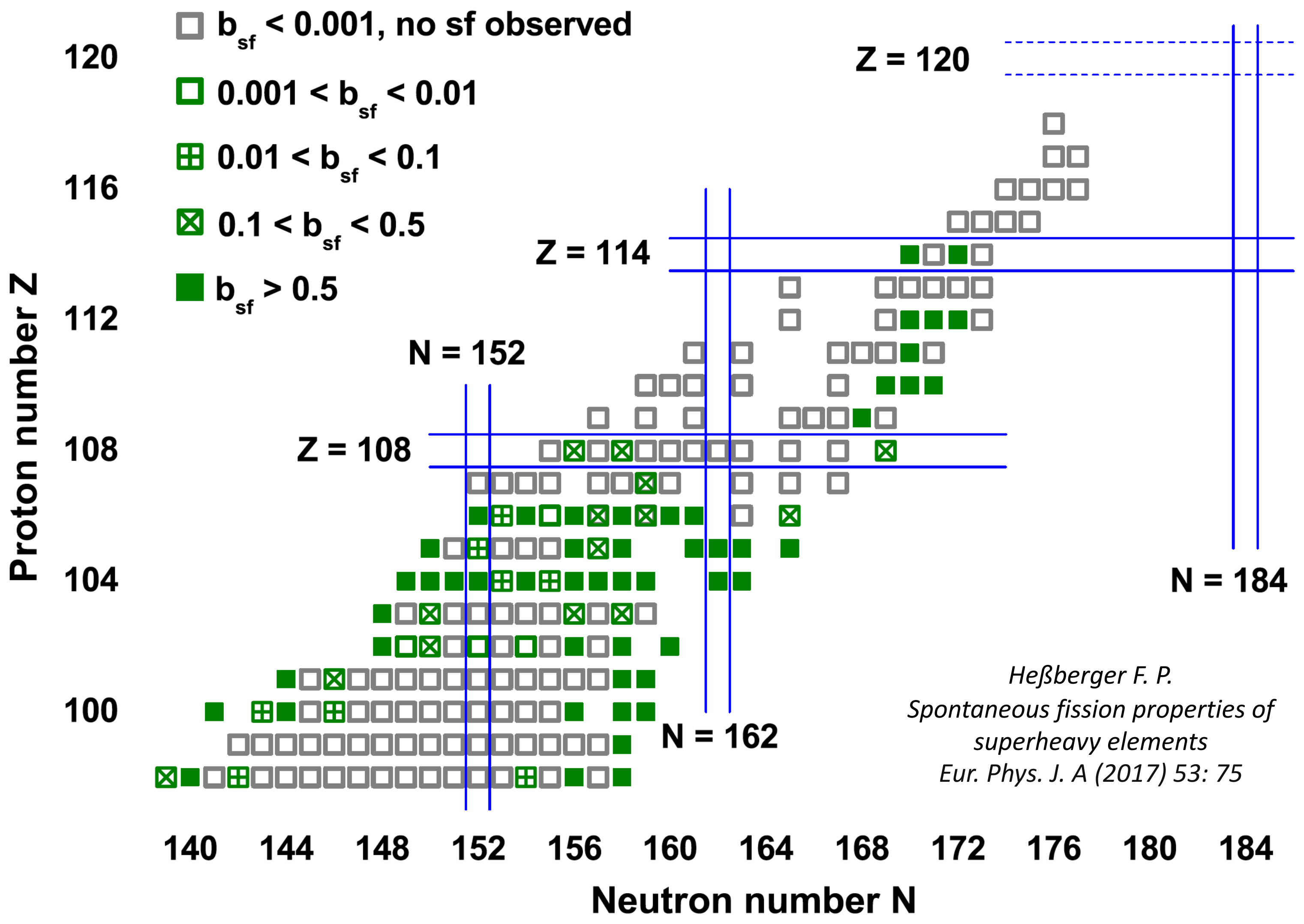
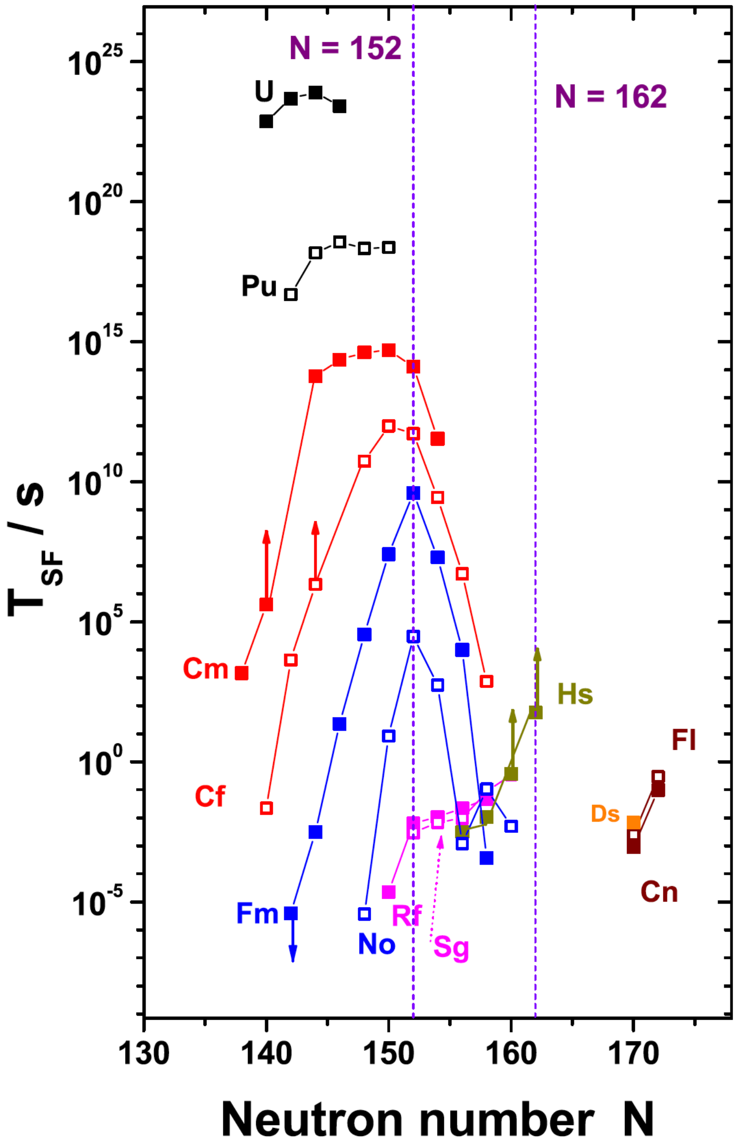
Sharm El-Sheikh, Egypt

Spontaneous Fission

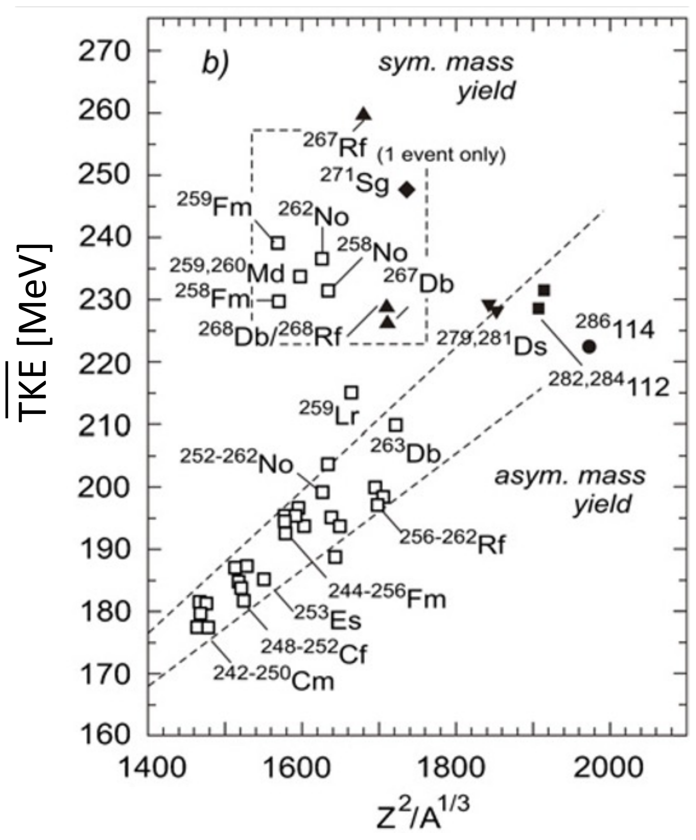
Flerov G. N. and Petrjak K. A.
Spontaneous Fission of Uranium
Phys. Rev. (1940) 58: 89



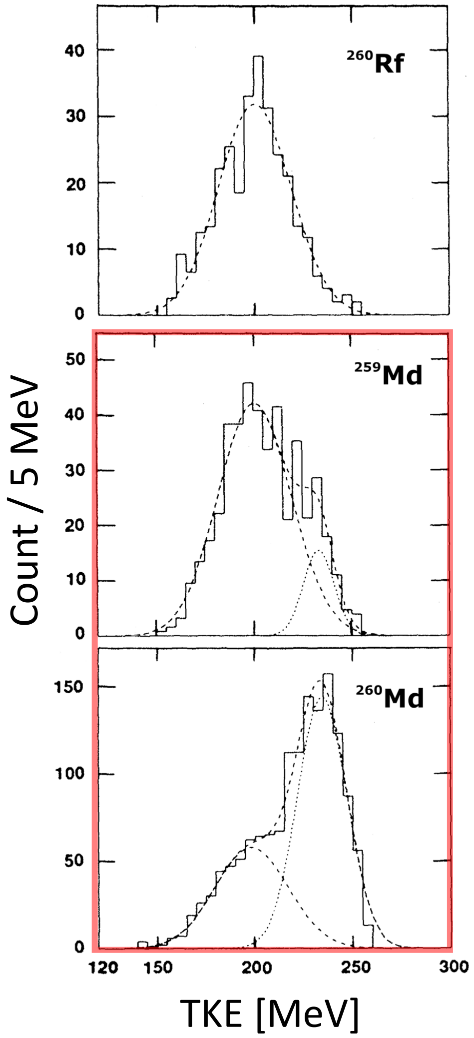
Heßberger F. P.
Spontaneous fission properties of superheavy elements
Eur. Phys. J. A (2017) 53: 75



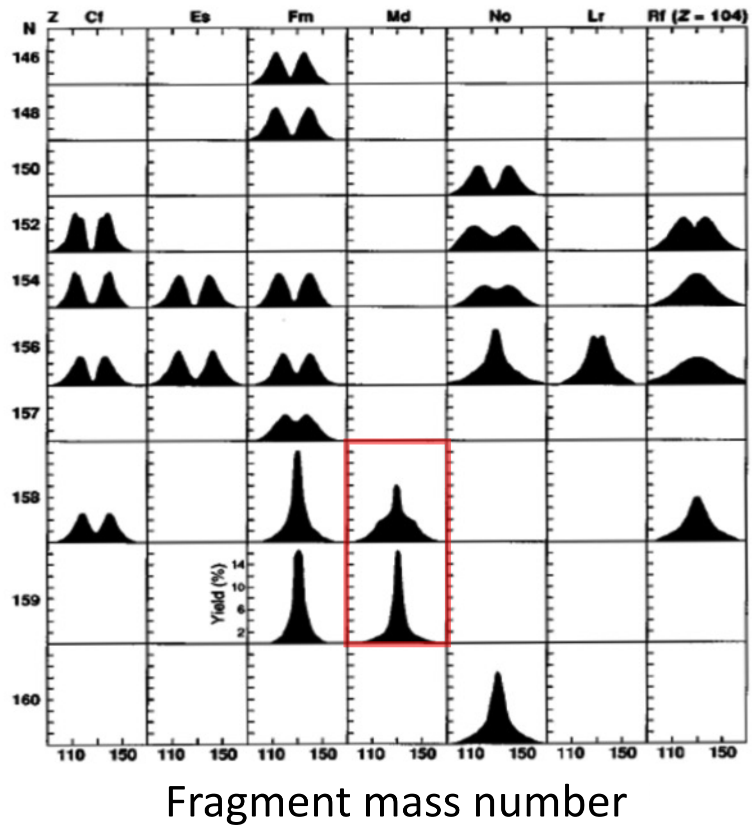
Fission Modes



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

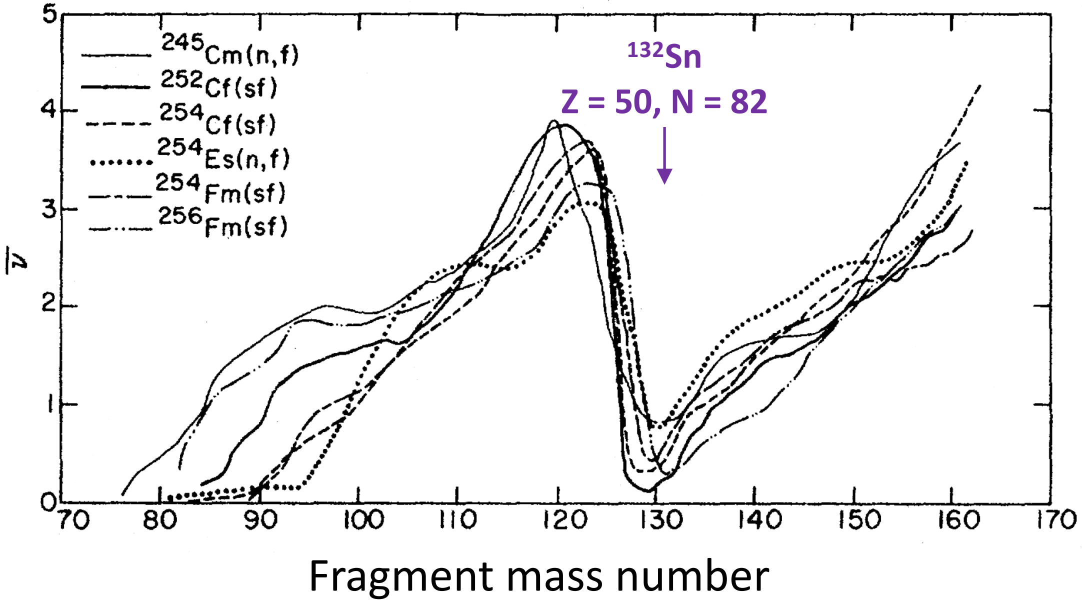
Prompt Neutrons

- **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**

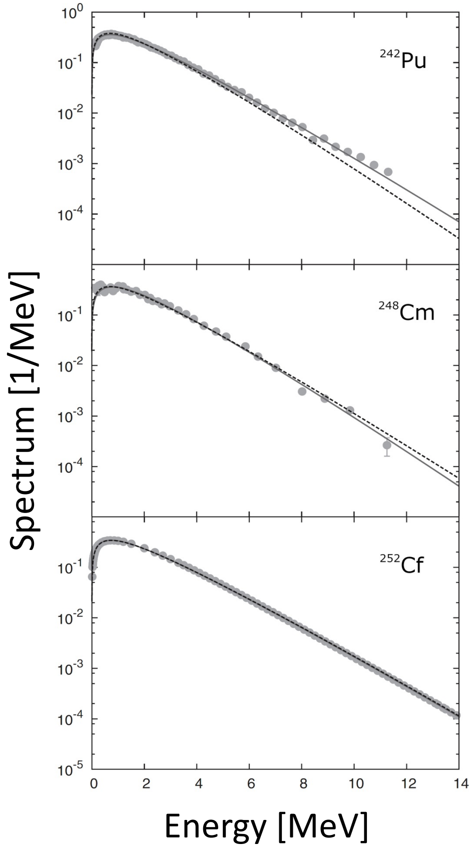
Different forms of energy (in MeV), released during SF of nuclei

Isotope	Kinetic	Excitation		Radioactive Decay		
		n	γ	$\boldsymbol{\beta}$	$\boldsymbol{\gamma}$	$\bar{\nu}_e$
^{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

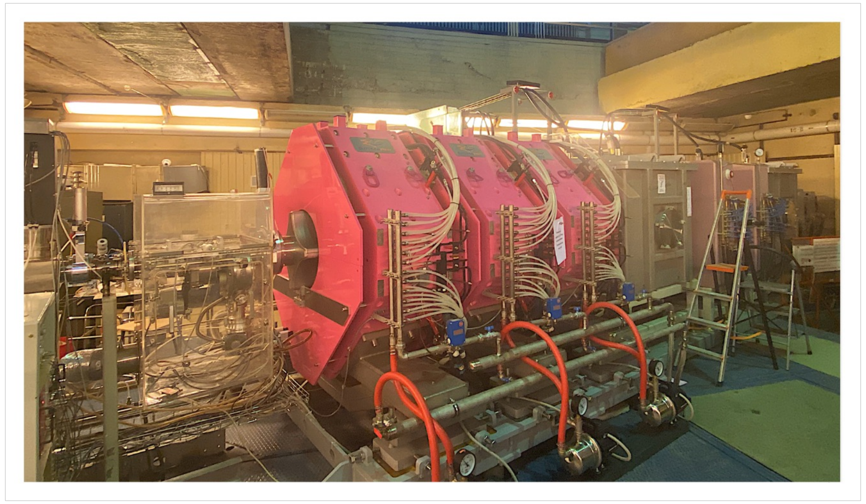


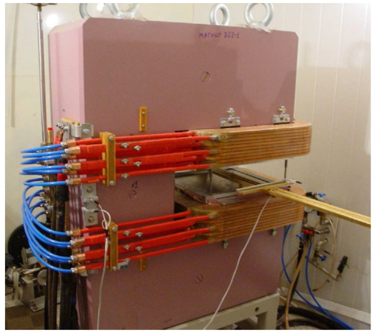
Gindler J.
Dependence of neutron yield on
fragment mass for several low-energy fissioning systems
PRC 19/5 (1979) P. 1806–1819

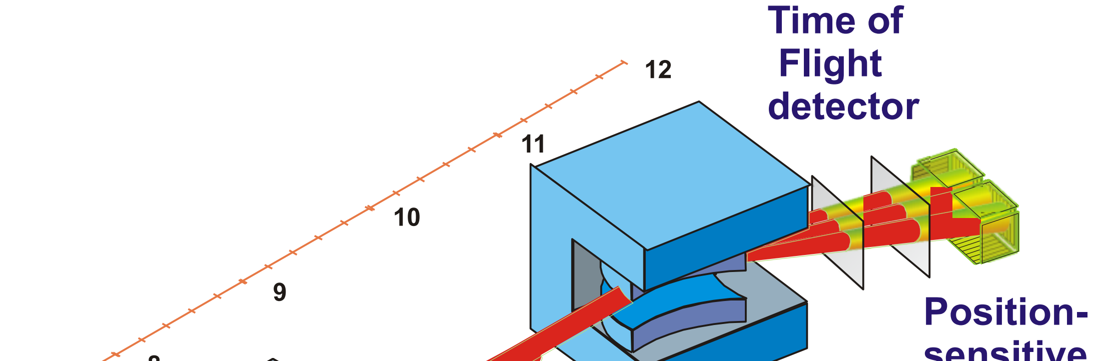


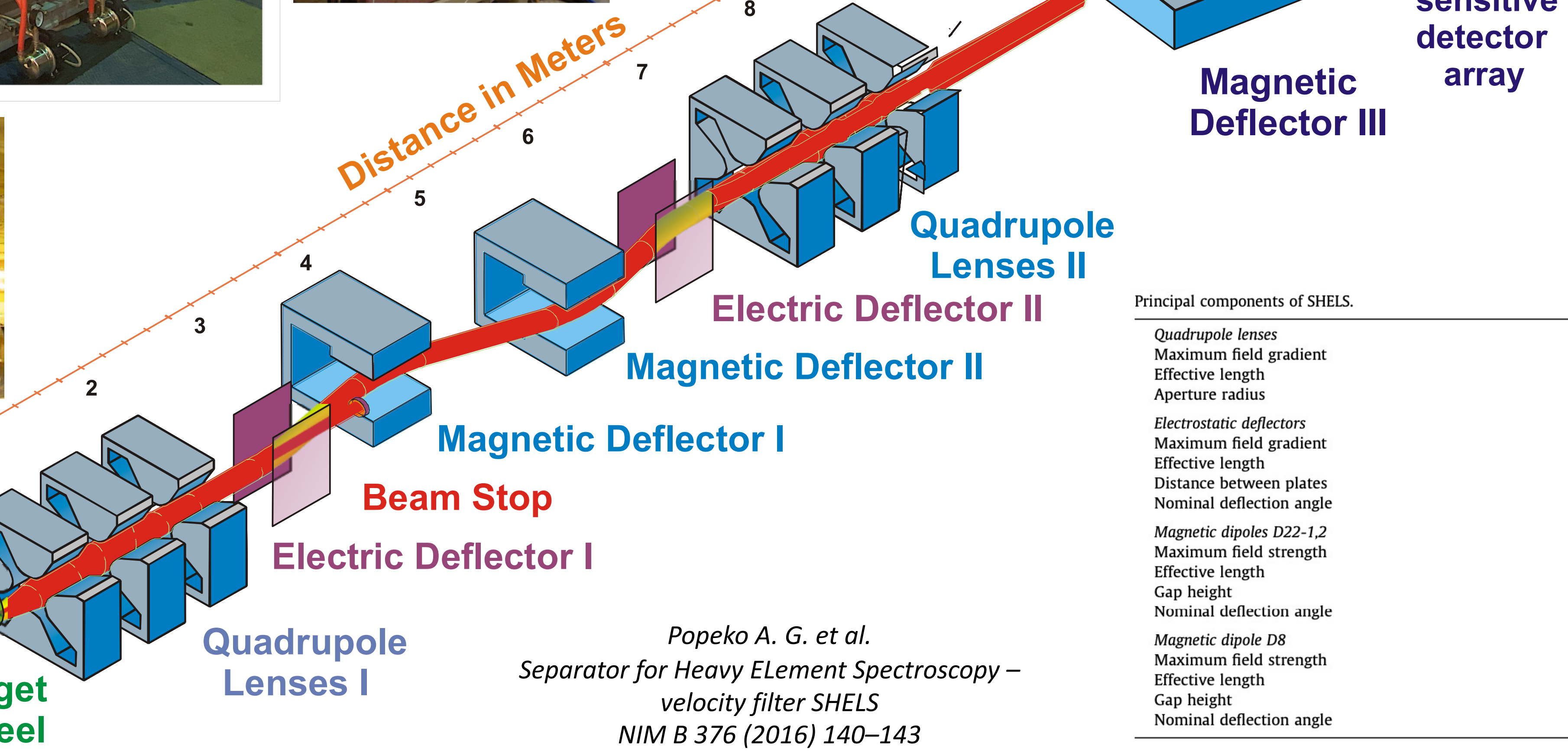
Iwamoto O.
Systematics of prompt fission
neutron spectra
JNST 45/9 (2008) P. 910–919

Separator for Heavy Element Spectroscopy – SHELS







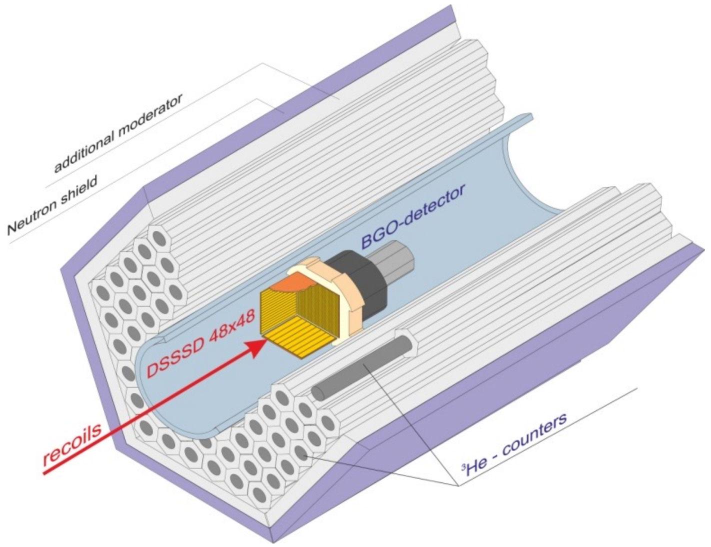


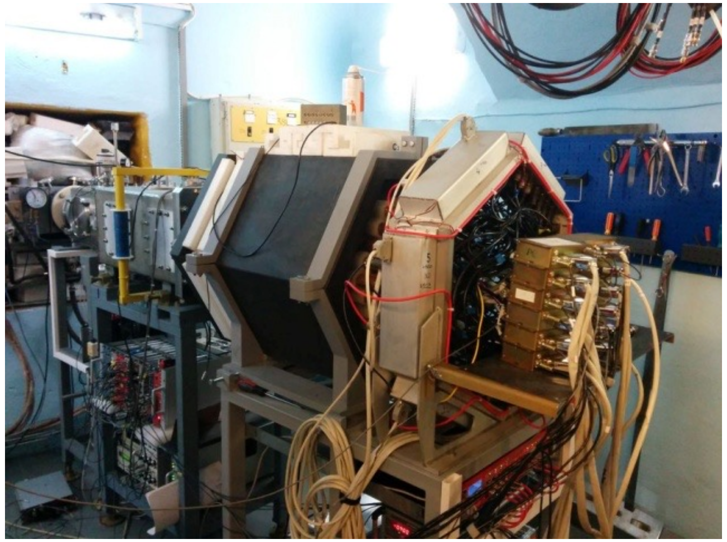
Popeko A. G. et al.
Separator for Heavy ELement Spectroscopy – velocity filter SHELS
NIM B 376 (2016) 140–143

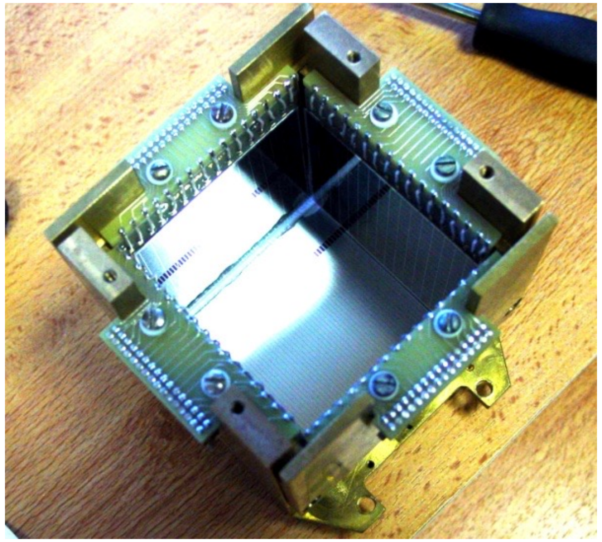
Principal components of SHELS.

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°

«Neutron Barrel»







Neutron detector:

- 54 ^{3}He-counters (⌀ 32 mm, 500 mm length, 7 atm. pressure)
- single neutron registration efficiency with ^{248}Cm-source is (45±1)%

Focal-plane 48×48-strip Si DSSD

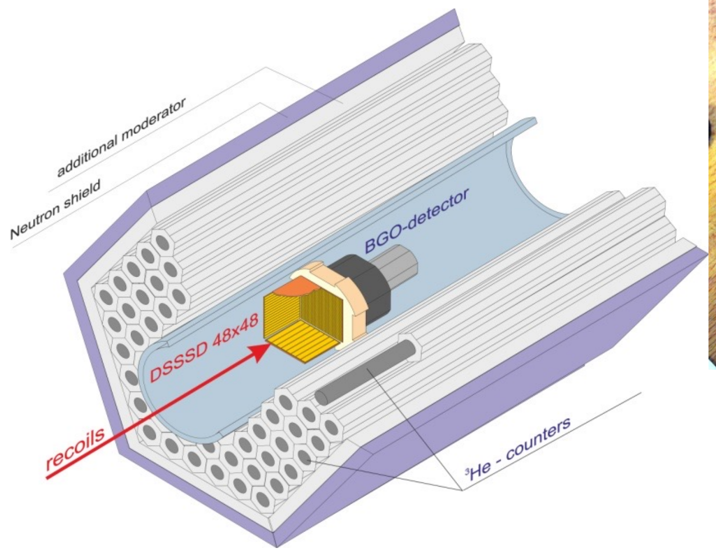
- active area is 58×58 mm
- resolution is 20 keV (for α with ~8 MeV)
- α registration efficiency is 50%, at least one fission fragment - 100%

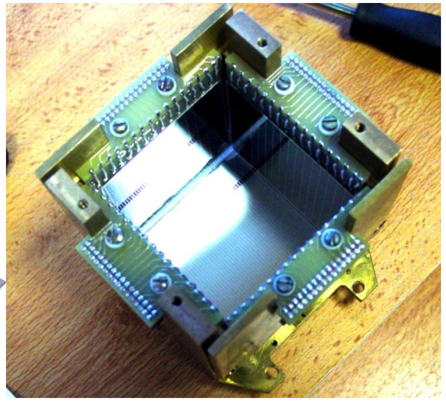
4 side 16-strip Si-detectors

Svirikhin A. I. et al.
A detector for studying the characteristics of spontaneous fission of short-lived heavy nuclei.
Instrum. Exp. Tech. 54/5 (2011) P. 644–648

Isaev A. V. et al.
Application of a double-sided stripped Si detector in the focal plane of the VASSILISSA separator.
Instrum. Exp. Tech. 54/1 (2011) P. 37–42

Upgrade of the Detector System

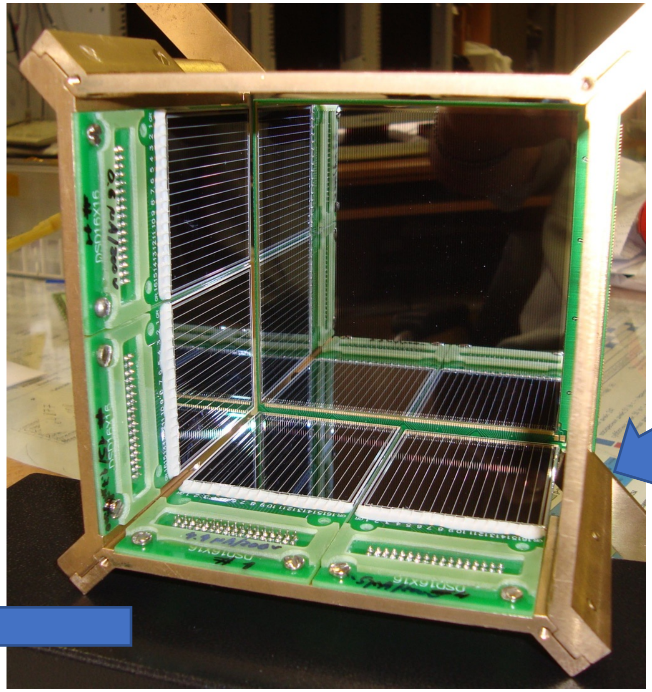




DSSD 60×60 mm

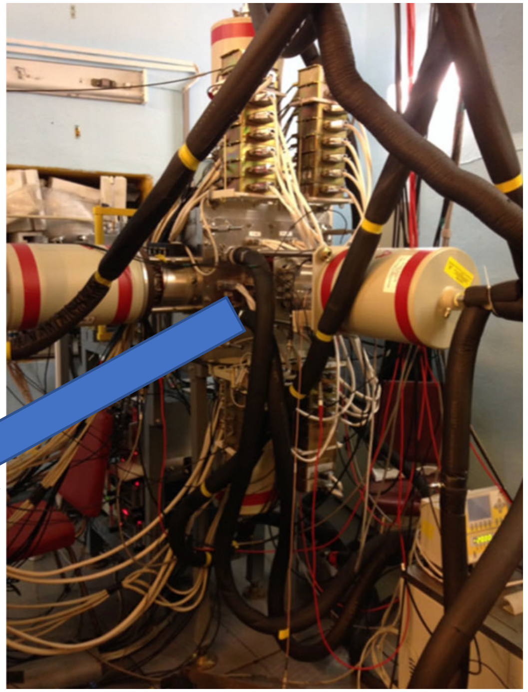
Cylindric vacuum chamber
⌀ 120 mm^2

Svirikhin A. I. et al.
A detector for studying the characteristics of spontaneous fission of short-lived heavy nuclei.
Instrum. Exp. Tech. 54/5 (2011) P. 644–648



New DSSD 100×100 mm

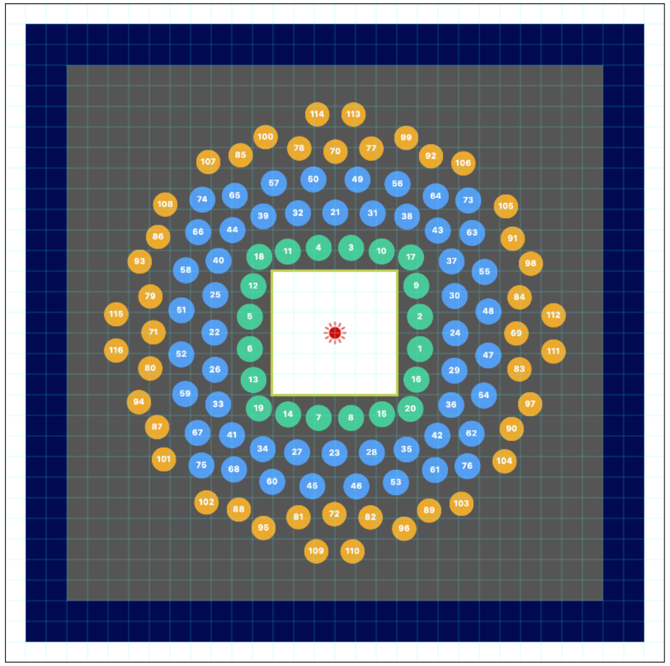
Isaev A. V. et al.
The SFiNx detector system.
PEPAN Letters 19 (2022) P. 37–45

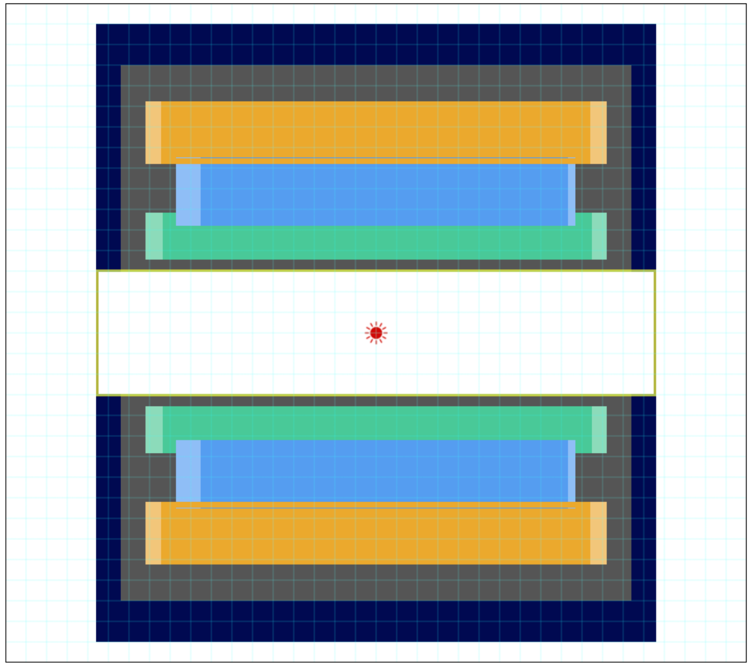


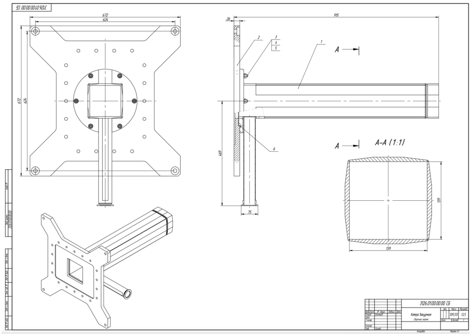
GABRIELA setup

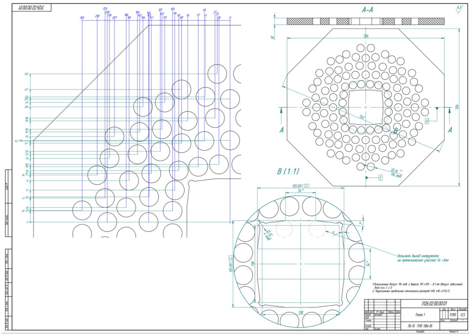
Chakma R. et al.
Gamma and conversion electron spectroscopy using GABRIELA.
Eur. Phys. J. A 56, 245 (2020).

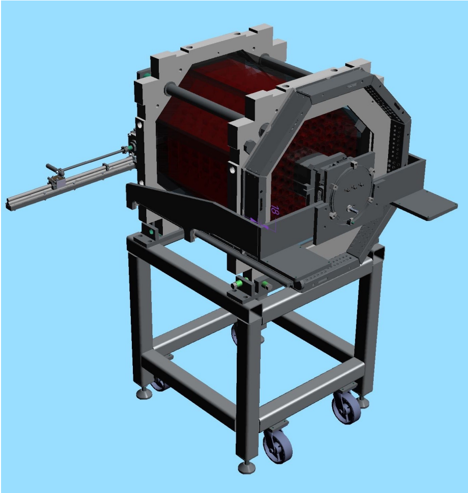
Optimal Geometry Search with MCNPX











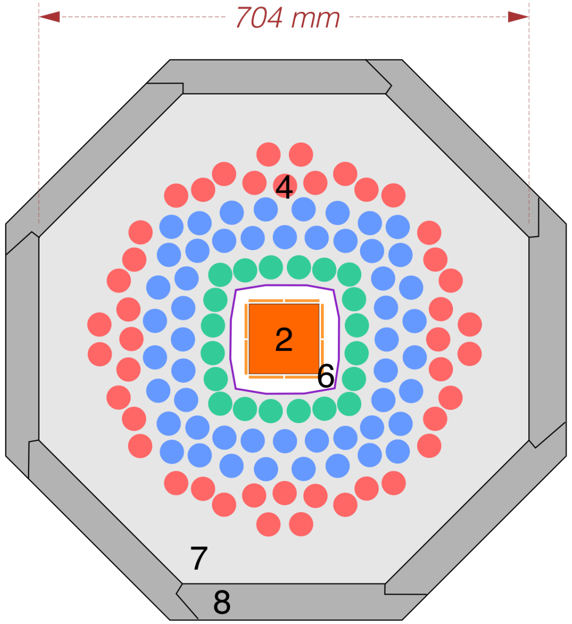
116 ^{3}He-counters (7 atm.)

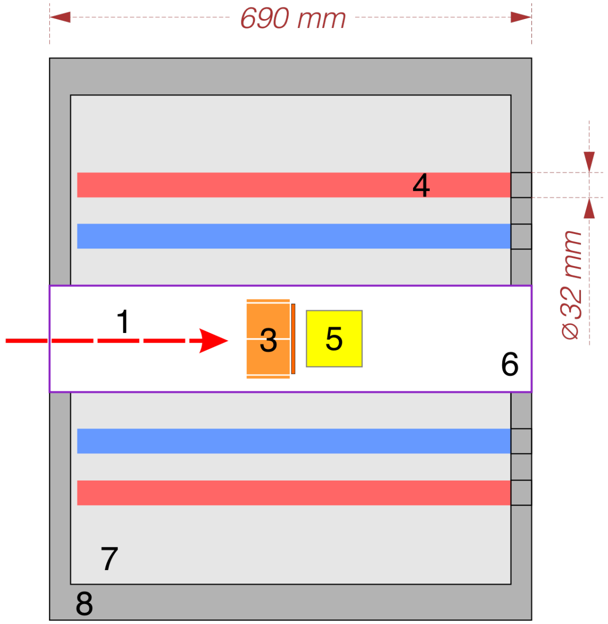
Layer	Count	Diameter, mm	Active length, mm	Voltage, V
1	20	32	530	1400
2	24	32	460	1775
3	28			
4	44	30	585	1500

SFiNx – Spontaneous Fission, Neutrons and x-rays

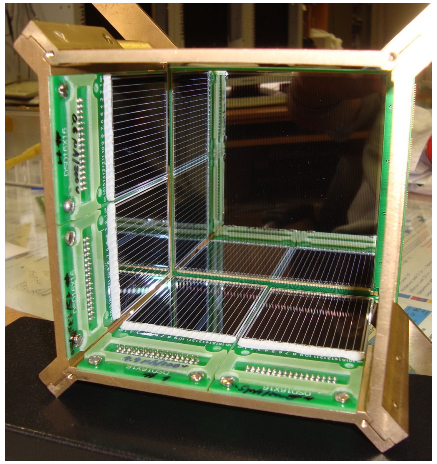
Isaev A. V. et al.
The SFiNx detector system
PEPAN Letters 19 (2022) P. 37–45

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





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

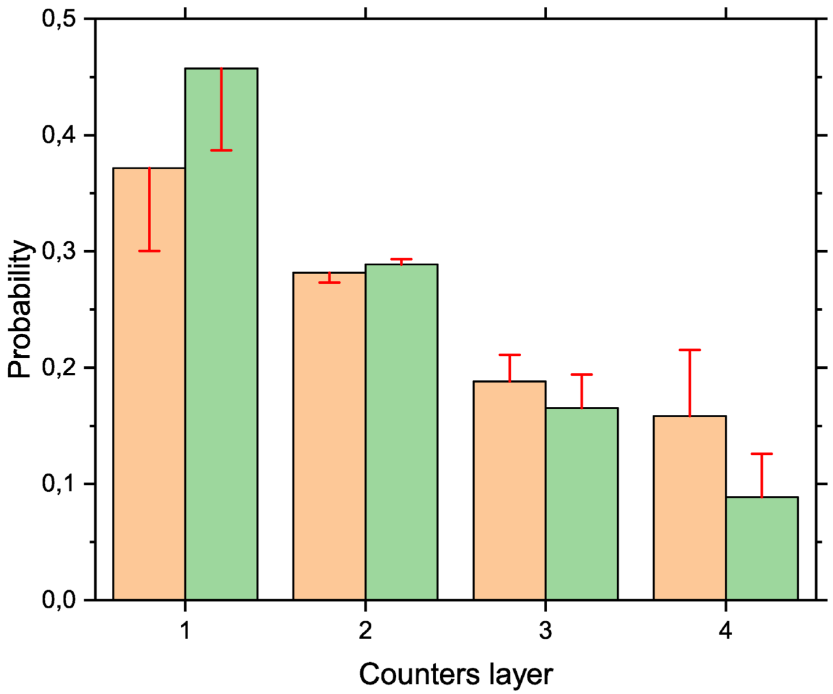


DSSD 100×100 mm
128×128-strips

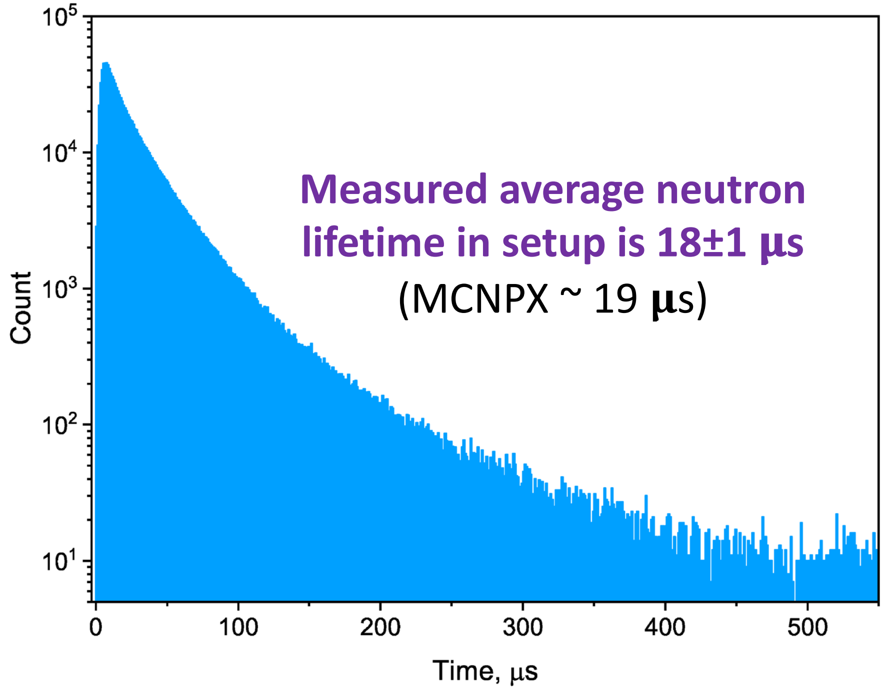
Tests with ^{248}Cm Source

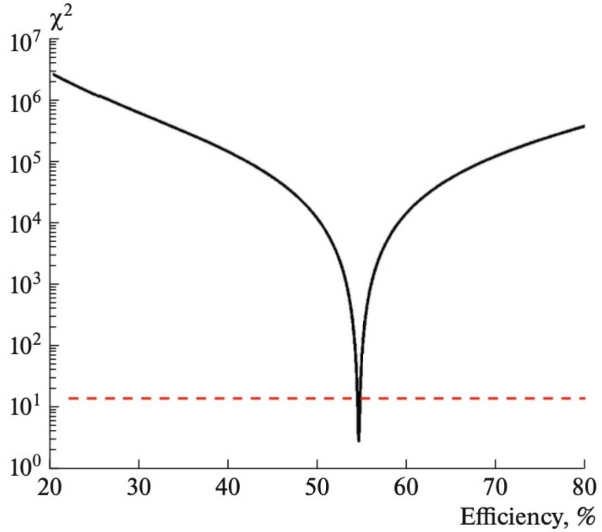
Measured single neutron registration efficiency of setup is 55±1%

(MCNPX 2.7.0 ~ 61%)



Measured neutron registration probabilities: per layer (left bars) and per counter of layer (right bars). Normalized.
Red sticks show deviations from the calculated values (MCNPX).





Charge collection time from counter, μs	20
Probability of random overlap of two signals in a separate counter	< 10^{-7}

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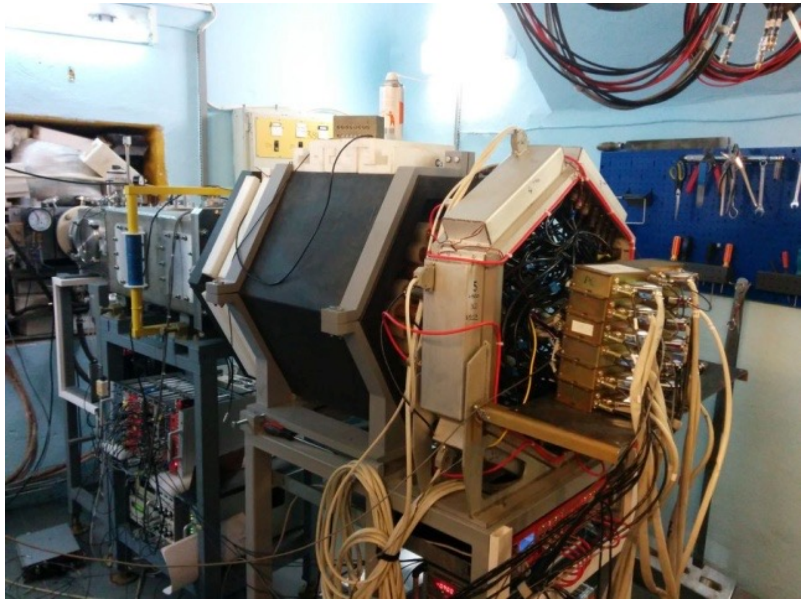
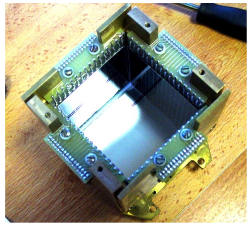
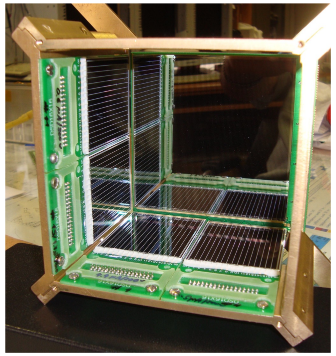
Comparison of Detector Systems

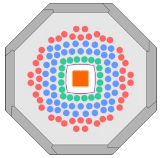






	«Neutron Barrel»	SFiNx
^{3}He-counters	54	116
Efficiency, %	45±1	**55±1**
Focal DSSD	48×48-strips 60×60 mm	128×128-strips 100×100 mm **(x2-3 ERs capture)**
Neutron average lifetime in detector, μs	23±1	**18±1**

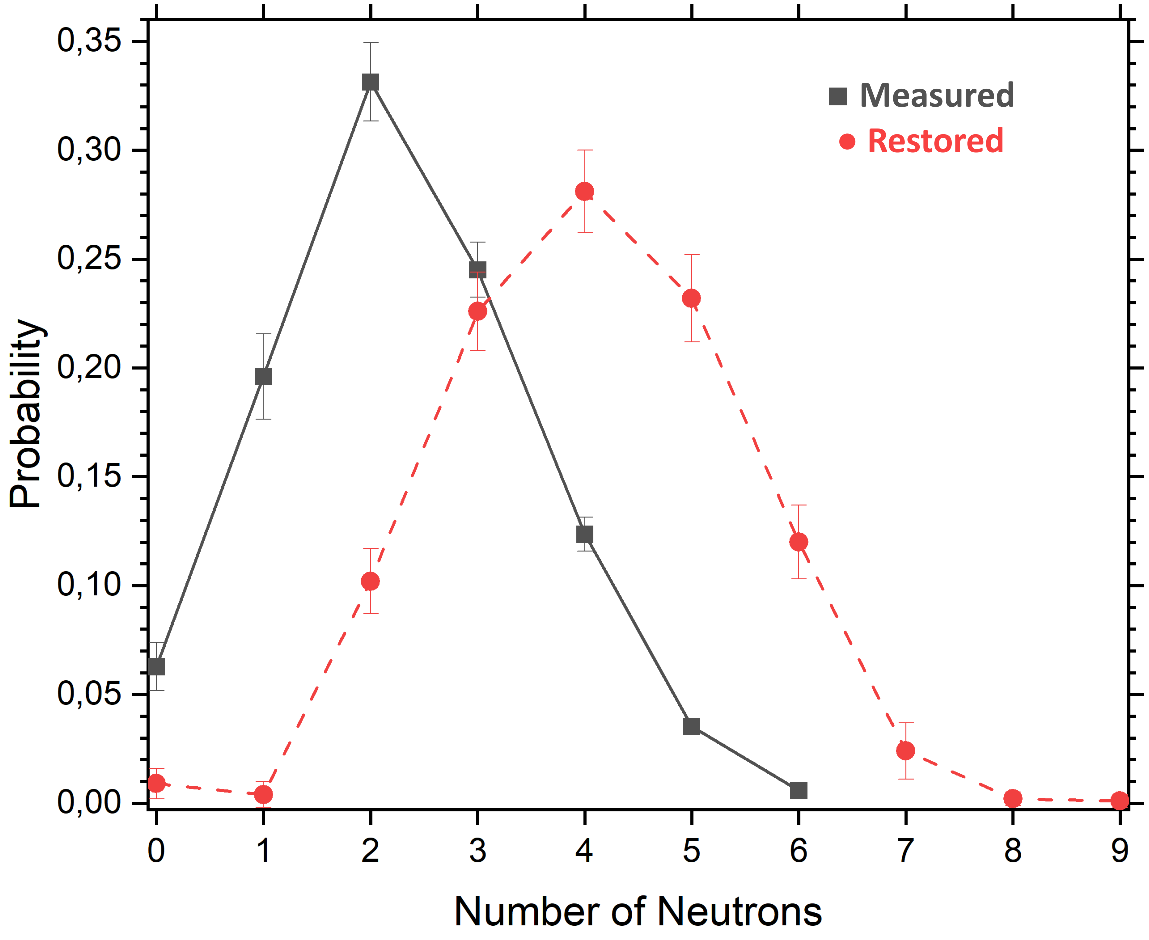
No 250



$b_{SF} = 1$

Isotope ^{250}No (2022)

Reaction	$^{48}Ca + ^{204}Pb$
Target PbS	450 $\mu g/cm^2$ 1.5 μm Ti; $^{204}Pb > 99.9\%$
$E_{1/2}$, MeV	215±2
σ_{max}, nb	~10
ε_n, %	55±1
Δt, μs	0 – 500
Σ_{SF}	**1357**
Σ_n	**3147**
$\bar{\nu}$	4.1±0.1
σ^2_{ν}	1.8
P_n	received for the first time
$T_{1/2}$, μs	**4.7±0.2** (ground) and **46±4**
b_α	Alpha-decay is not found



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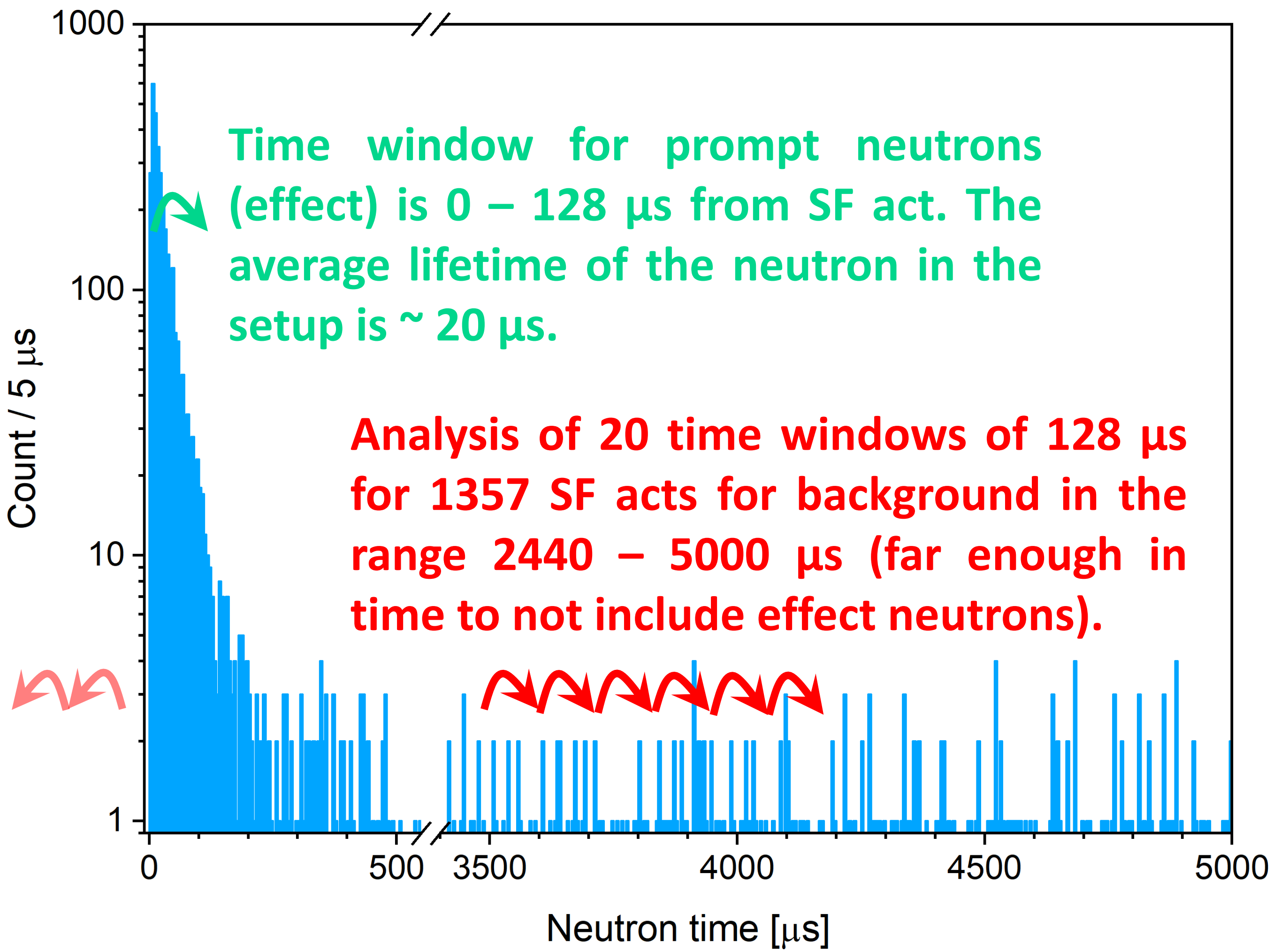
The Background Influence

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

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Unfolding of Multiplicity Distribution

- Since the detector efficiency is far from 100%, the measured neutron distribution is <u>highly distorted</u>
- Let's assume that the number of neutrons registered is a random variable that obeys the binomial distribution

$\boldsymbol{n}$ – maximum neutron multiplicity

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

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

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

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

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

$$\boldsymbol{y} = \boldsymbol{Kx}$$

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

A direct solution often doesn't make sense, when the <u>noise level is high</u> (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

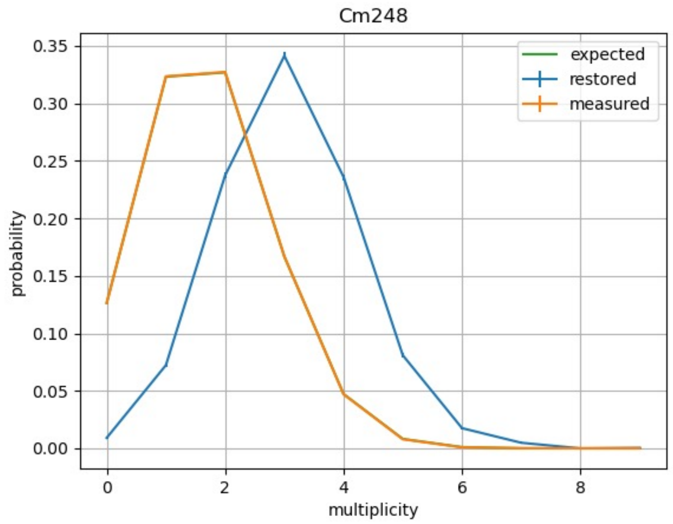
Mukhin R. S. et al. PEPAN Letters 18 (2021) P. 439–444
Turchin V.F., Kozlov V.P., and Malkevich M.S. Soviet Physics Uspekhi 13.6 (1971) P. 681–703
Turchin V.F. USSR Computational Mathematics and Mathematical Physics 7.6 (1967) P. 79–96

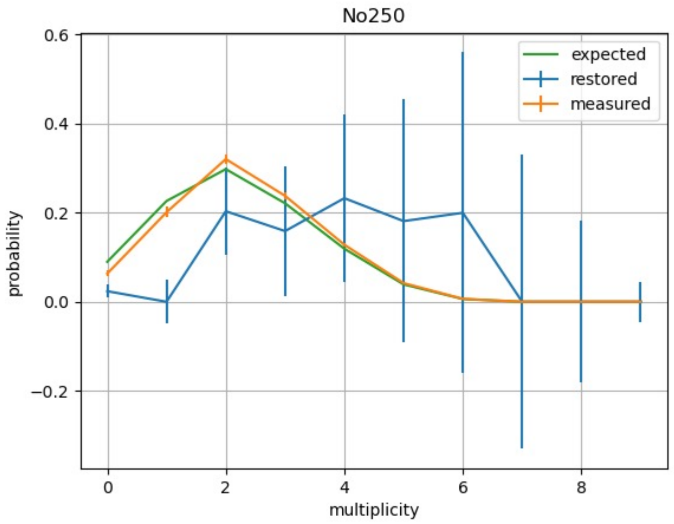
Direct Solution vs Tikhonov Regularization

$\varepsilon \sim 55\%$

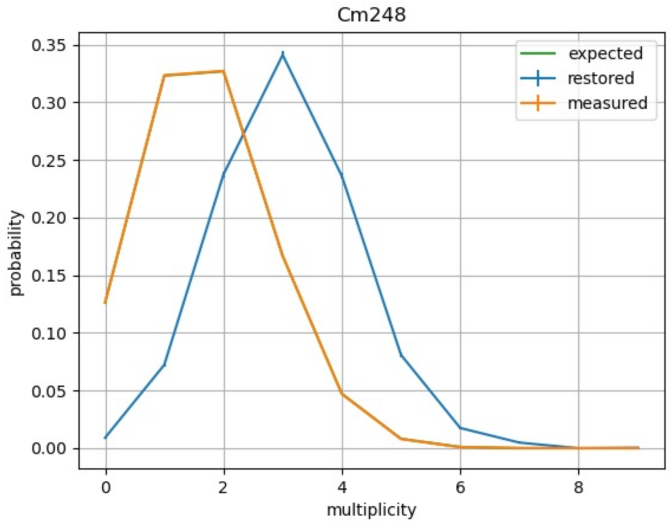
850k ^{248}Cm SF | **1357 ^{250}No SF**

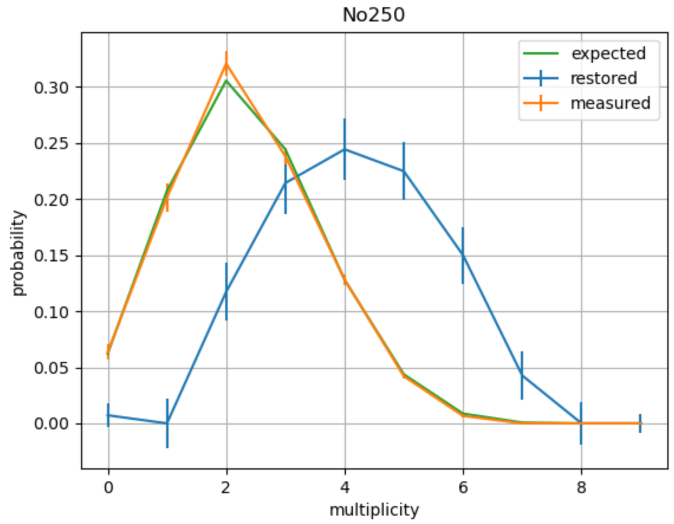
Direct Solution



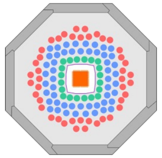


Regularization
$(\alpha = 89)$





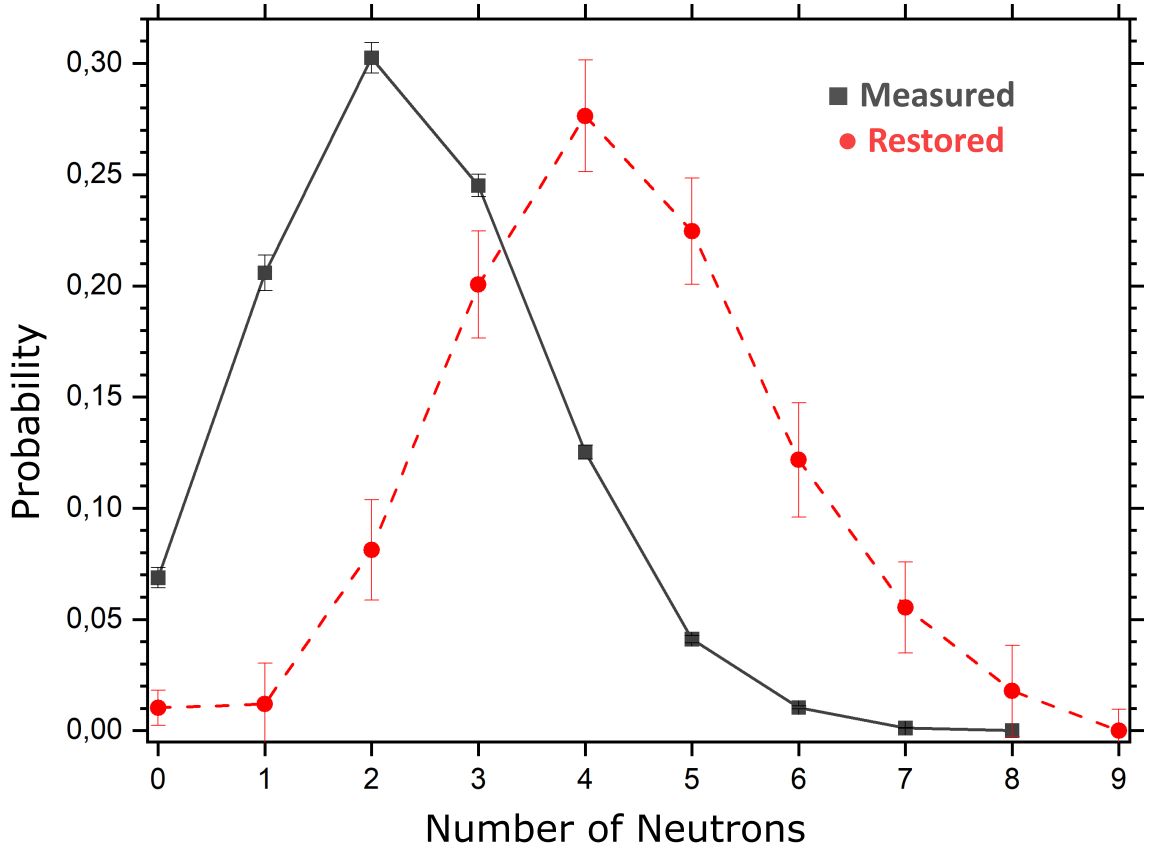
No 252



Isotope ^{252}No (2021)

$b_{SF} \approx 0,32$

Reaction	$^{48}Ca + ^{206}Pb$
Target PbS	350 $\mu g/cm^2$ 1.5 μm Ti; ^{206}Pb ~ 97%
$E_{1/2}$, MeV	215±2
σ_{max}, nb	~800
ε_n, %	55±1
Δt	1 ms – 25 s
Σ_{SF}	**3260**
Σ_n	**7574**
$\bar{\nu}$	4.25±0.09
σ^2_{ν}	2.1
P_n	values have been clarified
$T_{1/2}$, s	2.44±0.05



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The SFiNx detector system.
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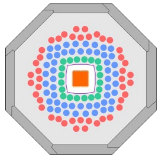
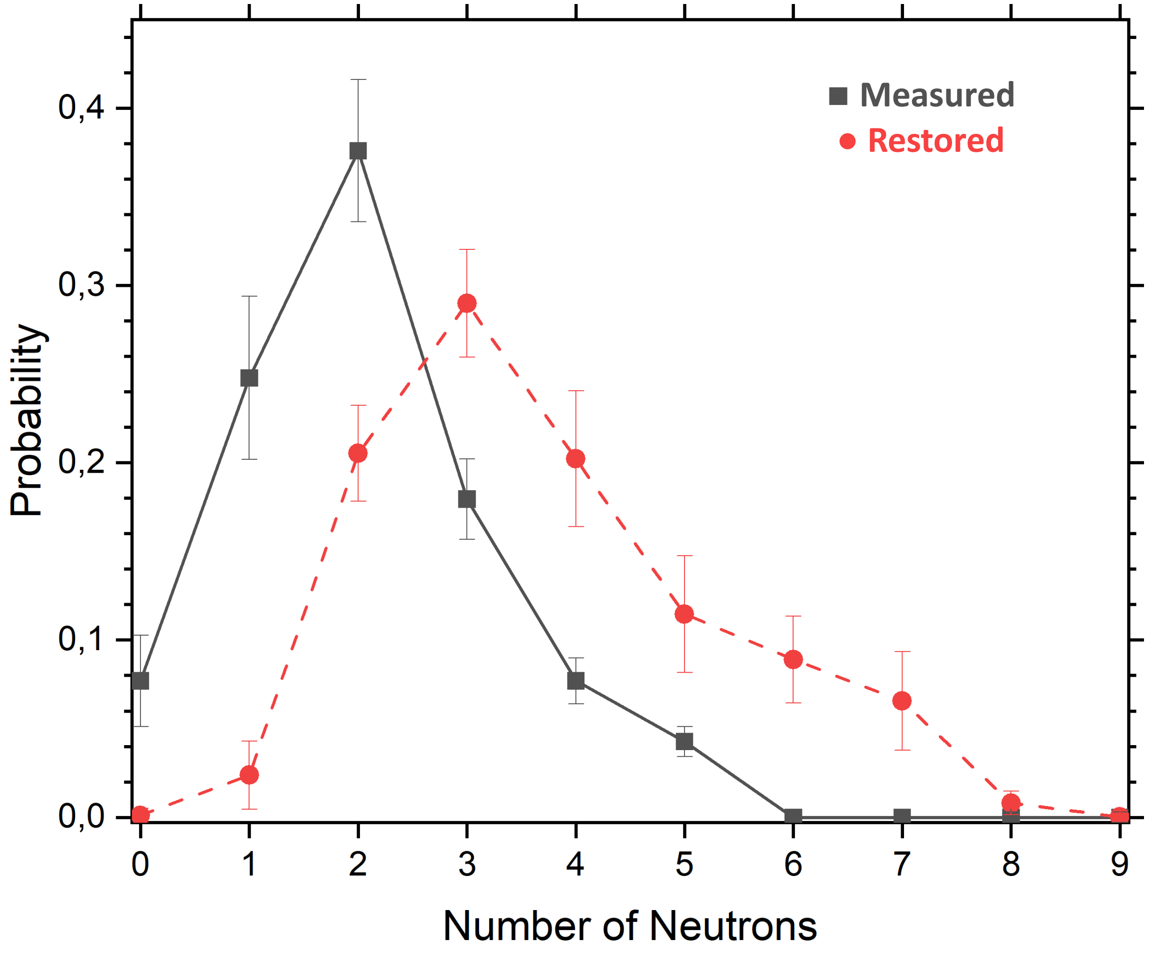
Fm 246



$b_{SF} \approx 0,06$

Isotope ^{246}Fm (2021)

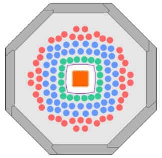
Reaction	^{40}Ar + ^{208}Pb
Target PbS	450 μg/cm^2 1.5 μm Ti; ^{208}Pb > 99%
$E_{1/2}$, MeV	183±3
σ_{max}, nb	~5
ε_n, %	55±1
Δt	30 ms – 15.4 s
Σ_{SF}	**235**
Σ_n	**488**
$\bar{\nu}$	3.79±0.30
σ_ν^2	2.1
P_n	values have been clarified
$T_{1/2}$, s	$1.50^{+0.08}_{-0.07}$
b_{SF}	0.061±0.005



Isaev A. V. et al.
Prompt neutron emission in the spontaneous fission of ^{246}Fm.
EPJ A 58.6 (2022)

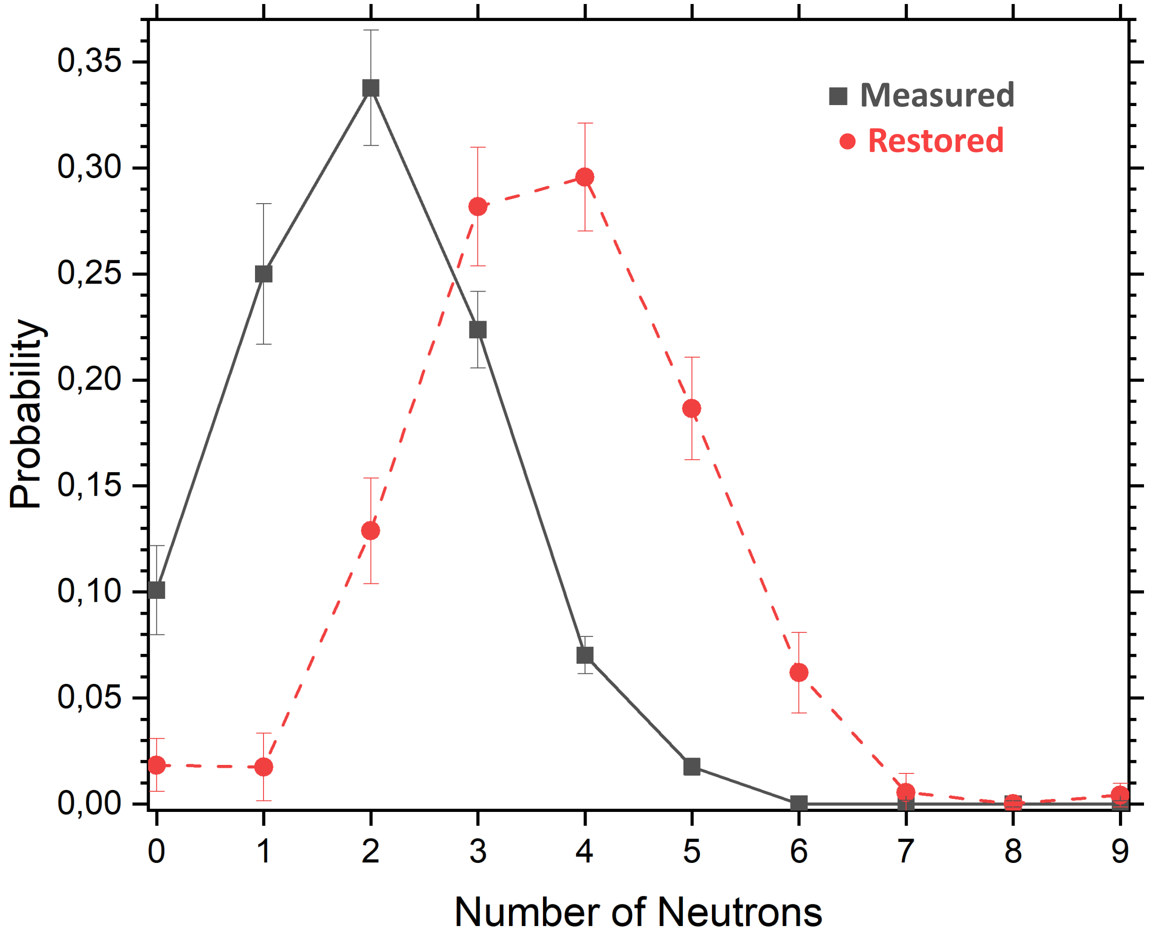
Fm 244

$b_{SF} < 1$

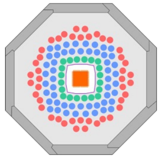


Isotope ^{244}Fm (2023)

Reaction	^{40}Ar + ^{206}Pb
Target PbS	350 $\mu g/cm^2$ 1.5 μm Ti; ^{206}Pb ~ 97%
$E_{1/2}$, MeV	186±3
σ_{max}, nb	~3
ε_n, %	55±1
Δt, ms	0 – 30
Σ_{SF}	**503**
Σ_n	**966**
$\bar{\nu}$	3.51±0.19
σ^2_ν	1.4
P_n	values have been clarified
$T_{1/2}$	3.7±0.1 ms
b_{SF}	~1



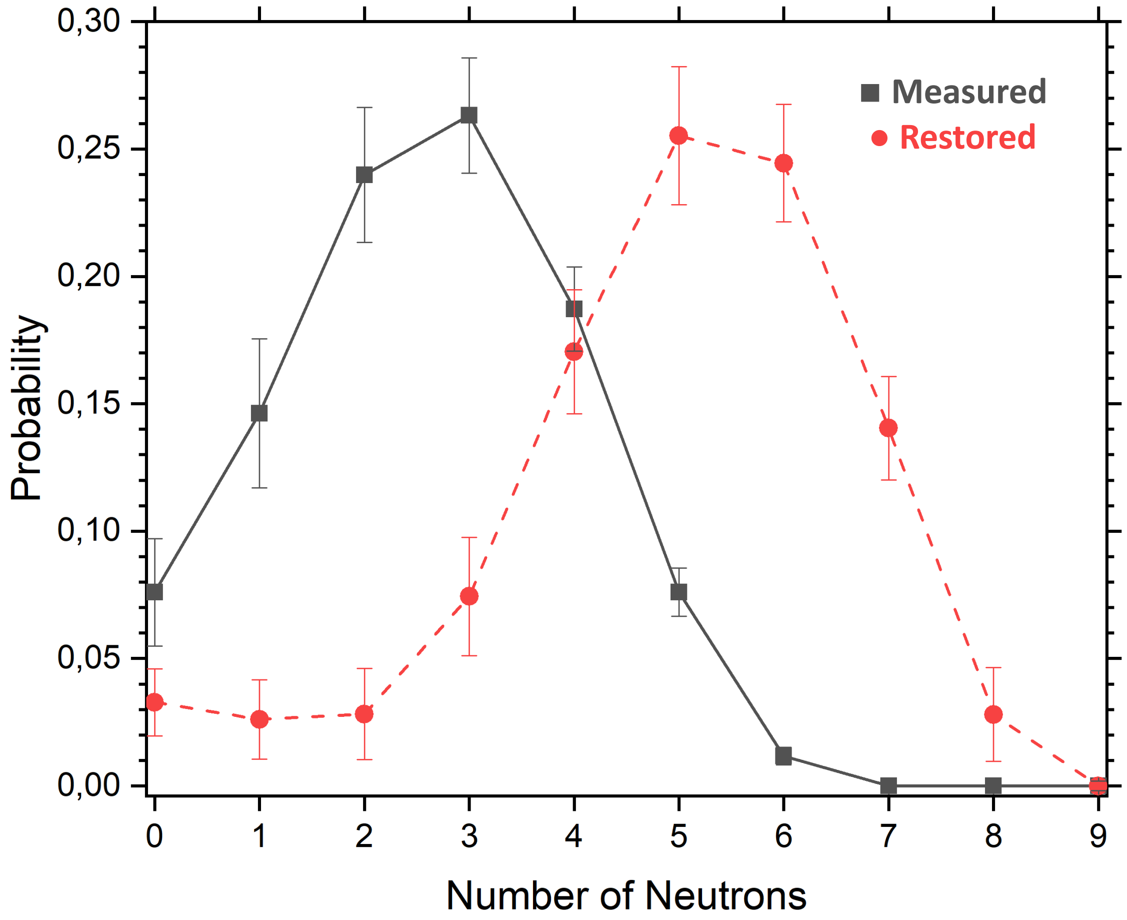
Preparing for publication



$b_{SF} < 0.3$

Isotope ^{260}Sg (2023)

Reaction	^{54}Cr + ^{207}Pb
Target PbS	350 μg/cm^2 2 μm Ti; ^{207}Pb > 99%
$E_{1/2}$, MeV	263±3
σ_{max}, nb	~0.3
ε_n, %	55±1
Δt, ms	0 – 40
Σ_{SF}	**171**
Σ_n	**447**
$\bar{\nu}$	4.8±0.4
σ_ν^2	2.6
P_n	received for the first time
$T_{1/2}$, ms	~4



Preliminary results

2nd experiment is planned for May 2024

Agreement Between Theory and Experiment

GEF

(General Description of Fission Observables)

Schmidt K.-H. et al. Nuclear Data Sheets 131 (2016), P. 107–221

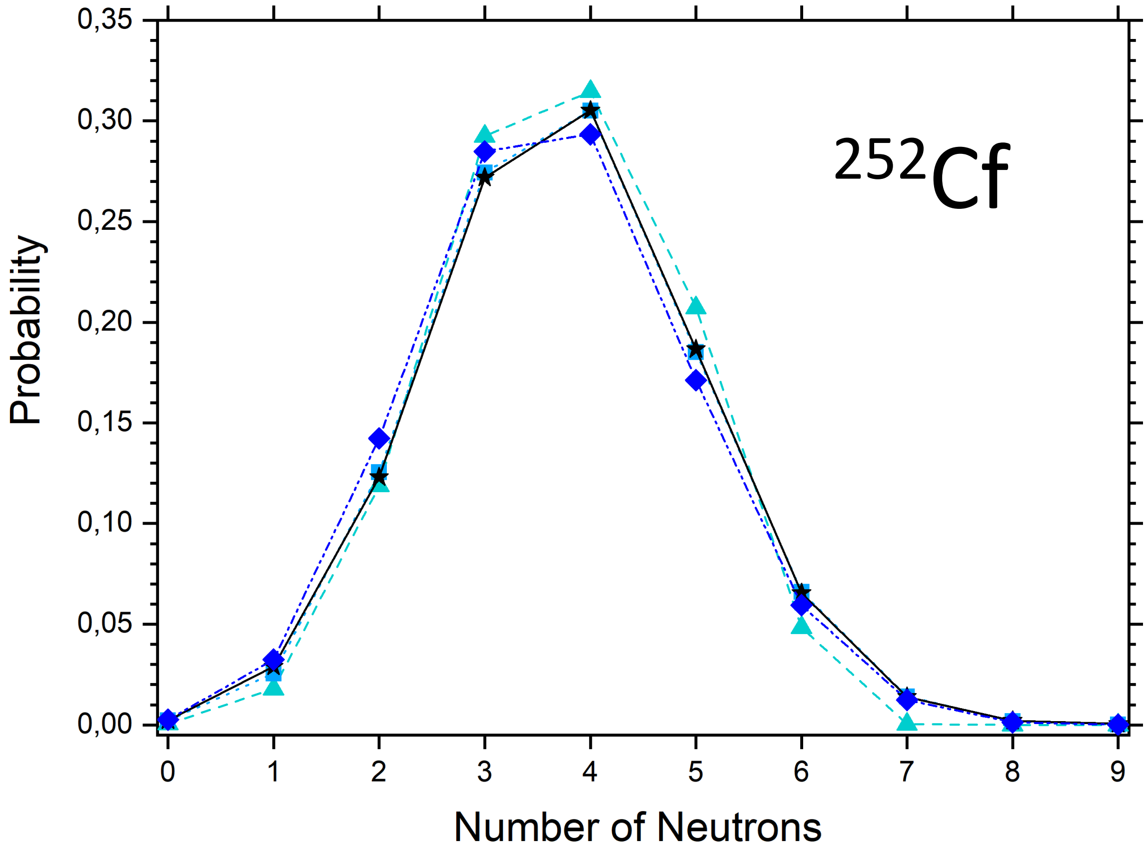
ISP

(Improved Scission Point Model)

Andreev A. V. et al. EPJ A 30/3 (2006), P. 579–589

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

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



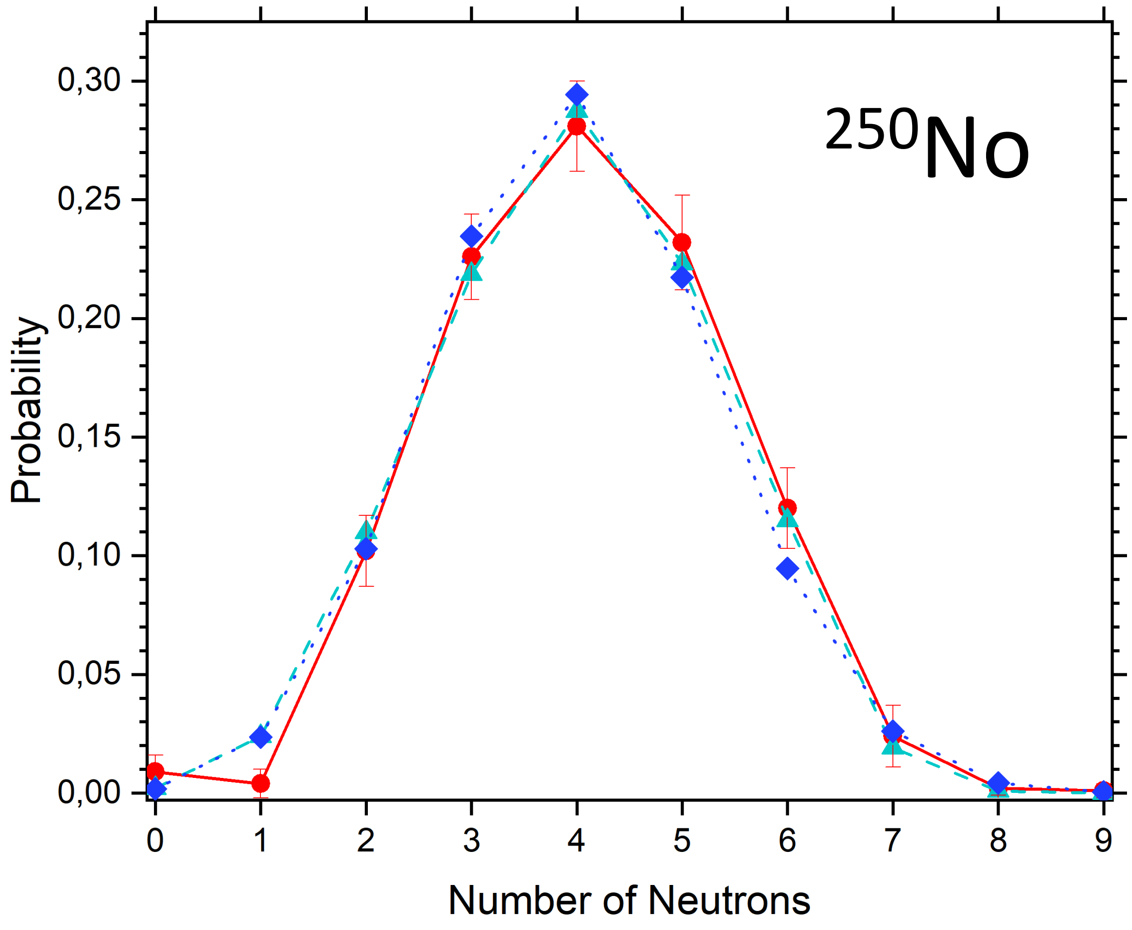
■ Holden, Zucker. 1986 (3.76±0.01)

★ Vorobyev, et al. 2005 (3.76±0.03)

▲ ISP (3.72±0.23)

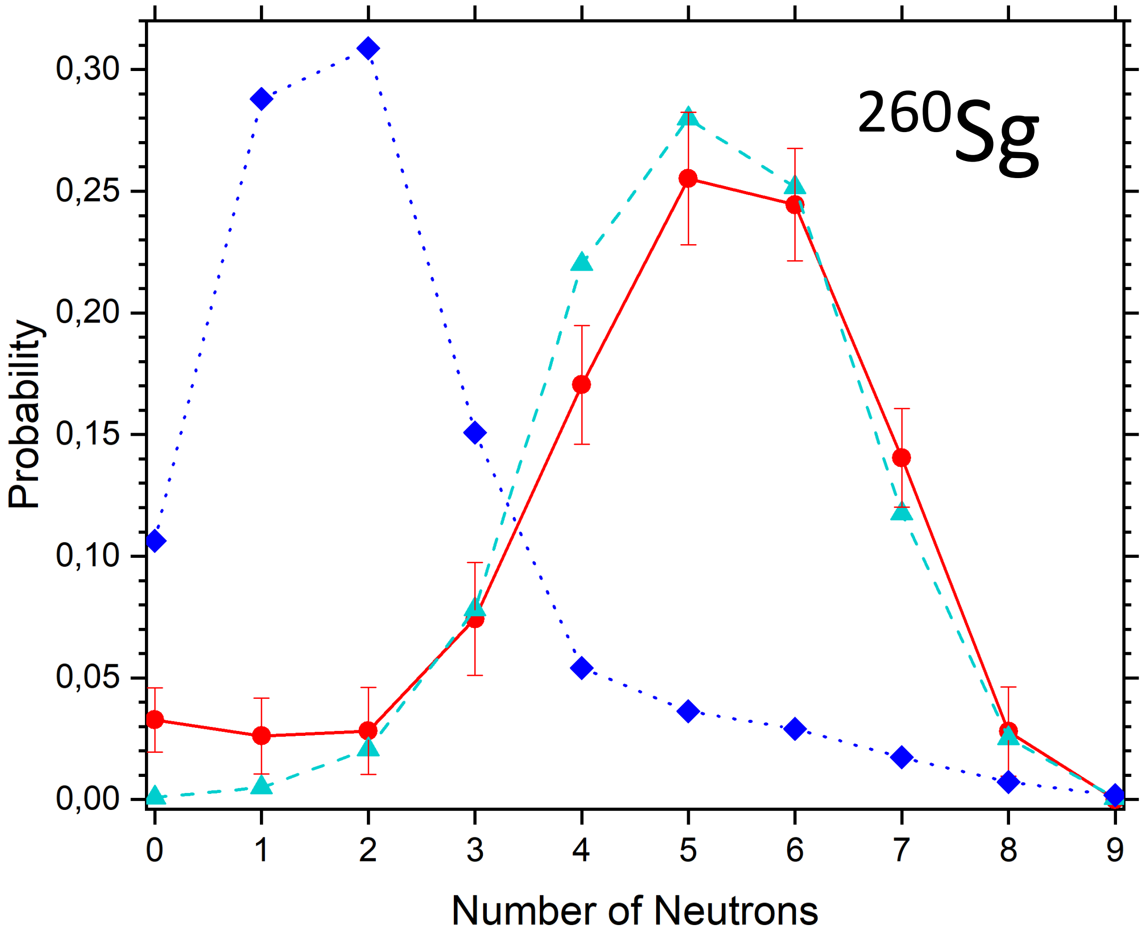
◆ GEF (3.66±0.03)

Agreement Between Theory and Experiment



● SFiNx (4.1±0.1) / CPC-0091 (2024)

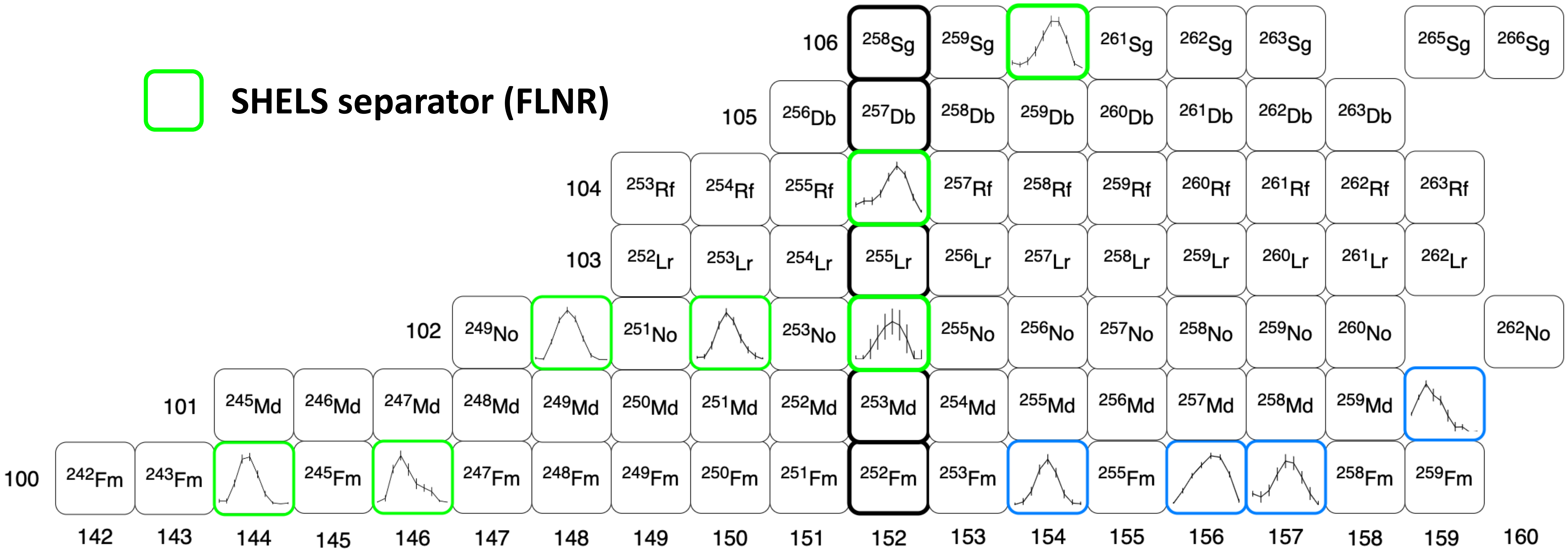
▲ ISP (4.0)
◆ GEF (4.0)



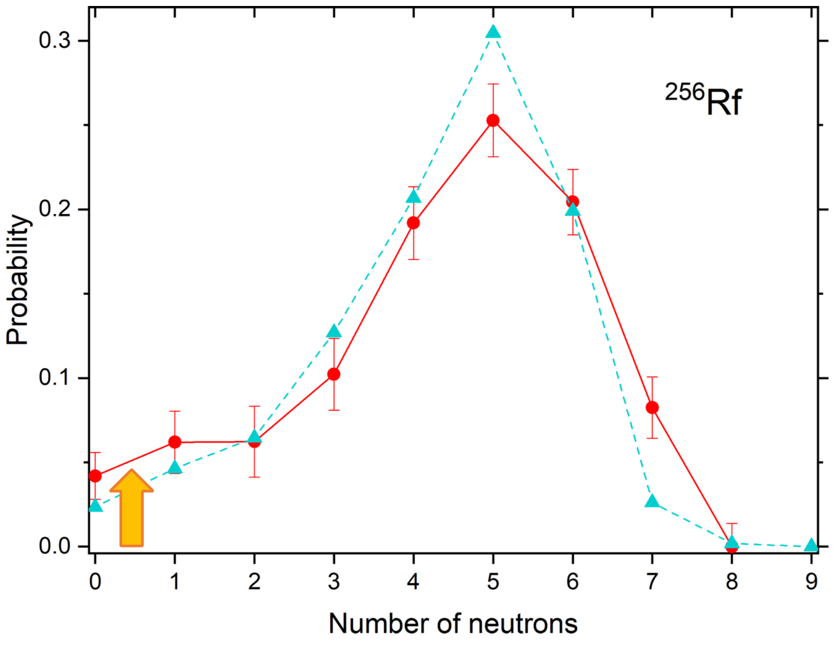
● SFiNx (4.9±0.2) / Preliminary results

▲ ISP (5.1)
◆ GEF (2.1)

Shapes of the Prompt Neutron Multiplicity Distributions



Features of the Prompt Neutron Multiplicity

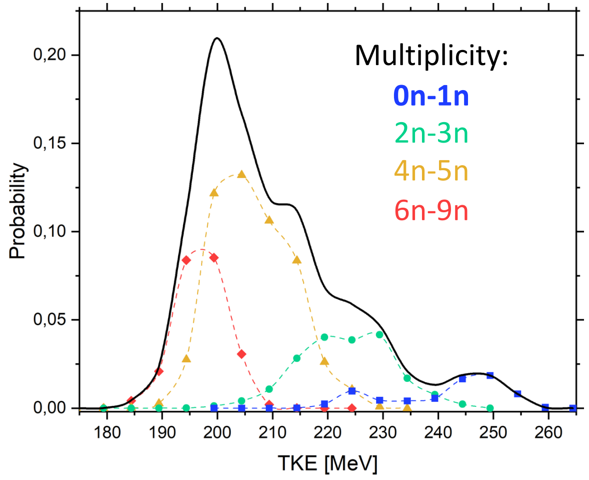


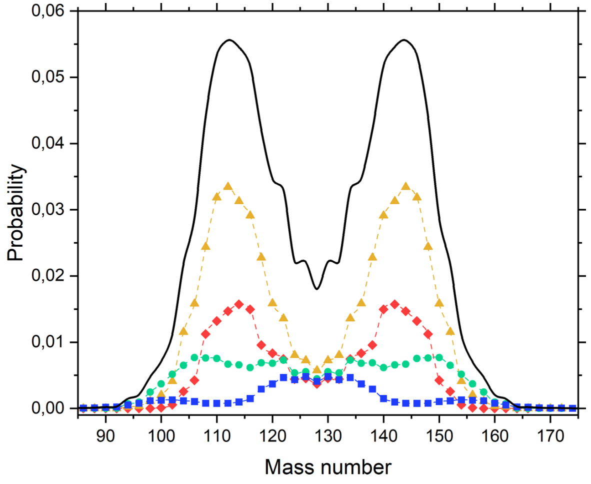
● FLNR, experiment (4.30±0.09)

▲ BLTP, ISP model (4.3)

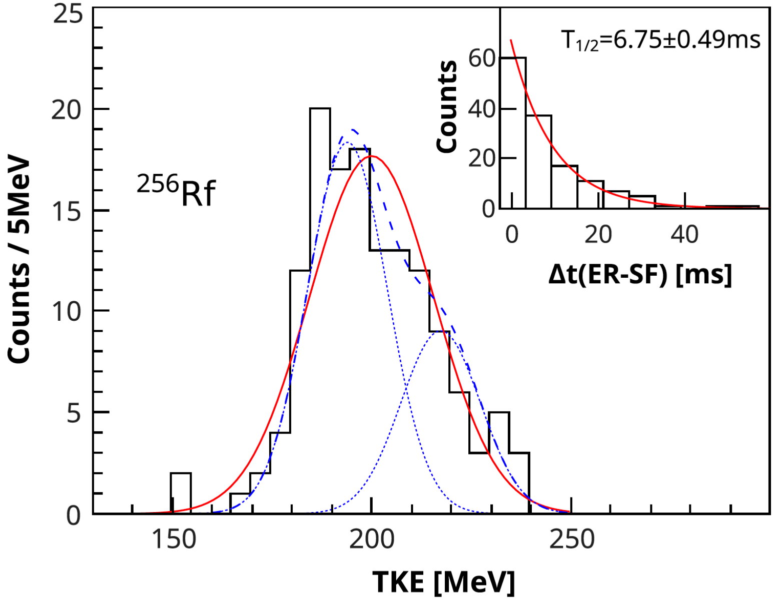
Isaev, A. V. et al.,
Structure of the prompt neutron multiplicity distribution in the spontaneous fission of ^{256}Rf.
Physics Letters B 843 (2023) 138008

ISP model



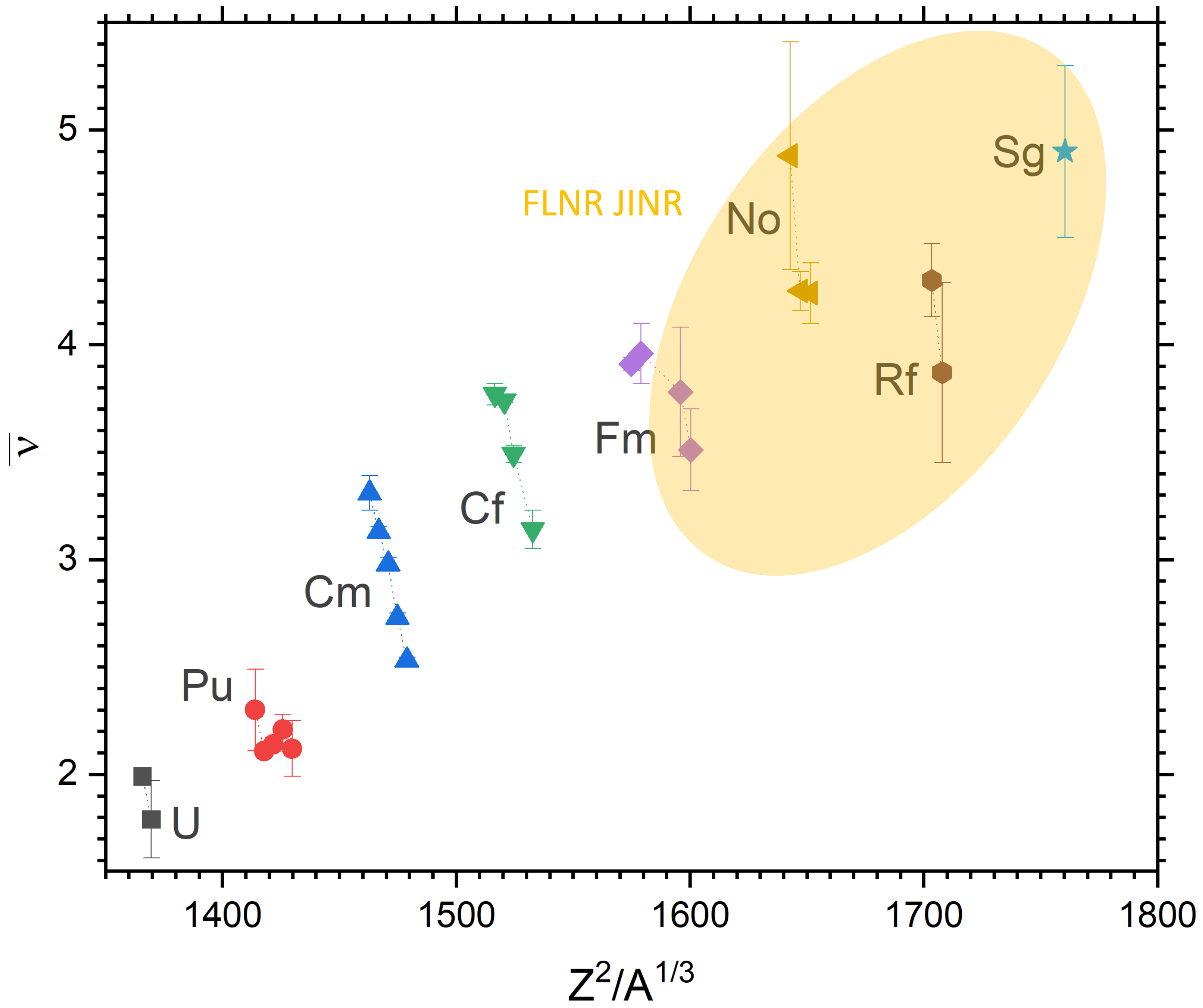


Experiment

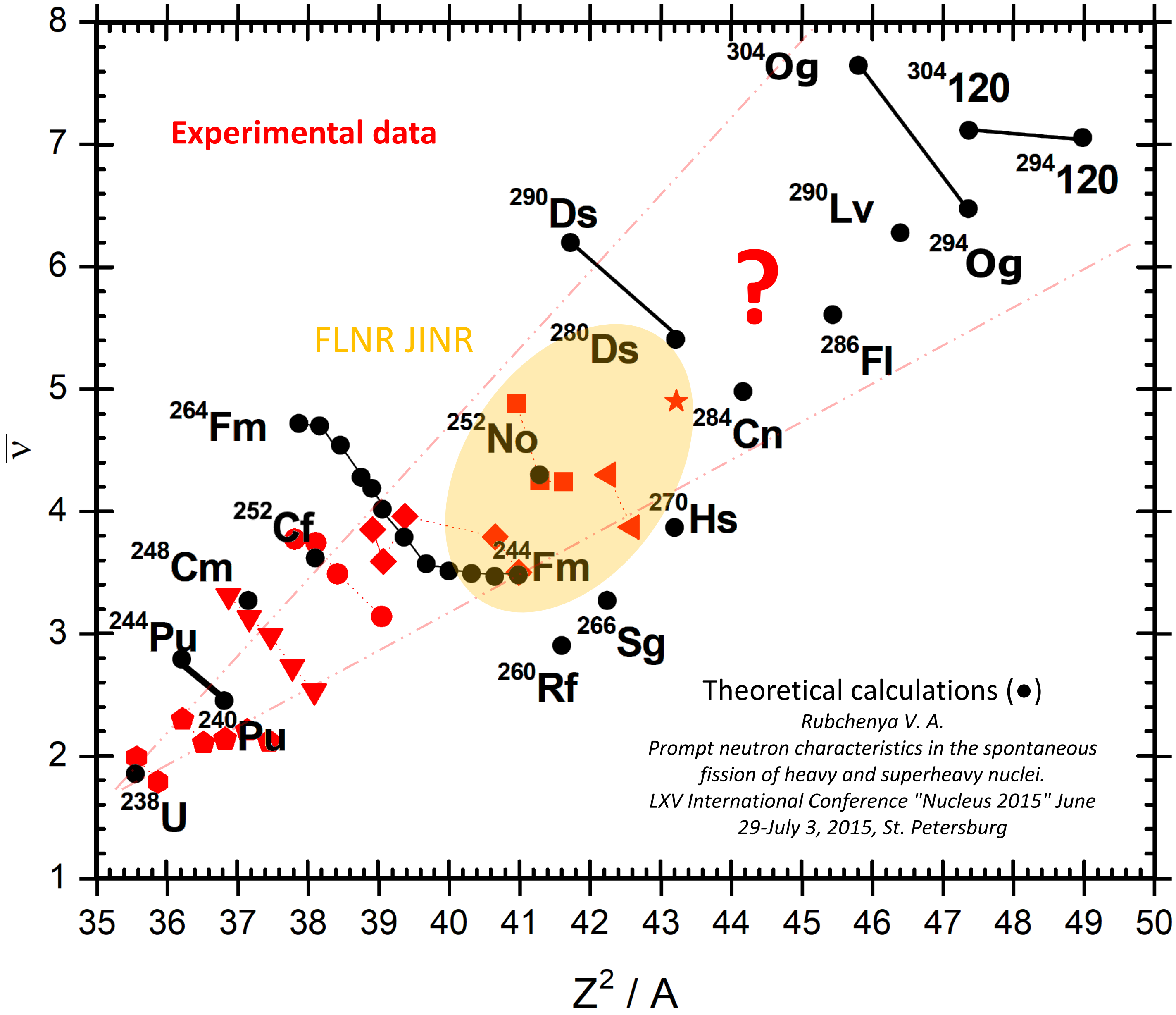


Mosat P. et al.
K isomerism in ^{255}Rf and total kinetic energy measurements for spontaneous fission of ^{255,256,258}Rf
Phys. Rev. C 101 (2020) 034310

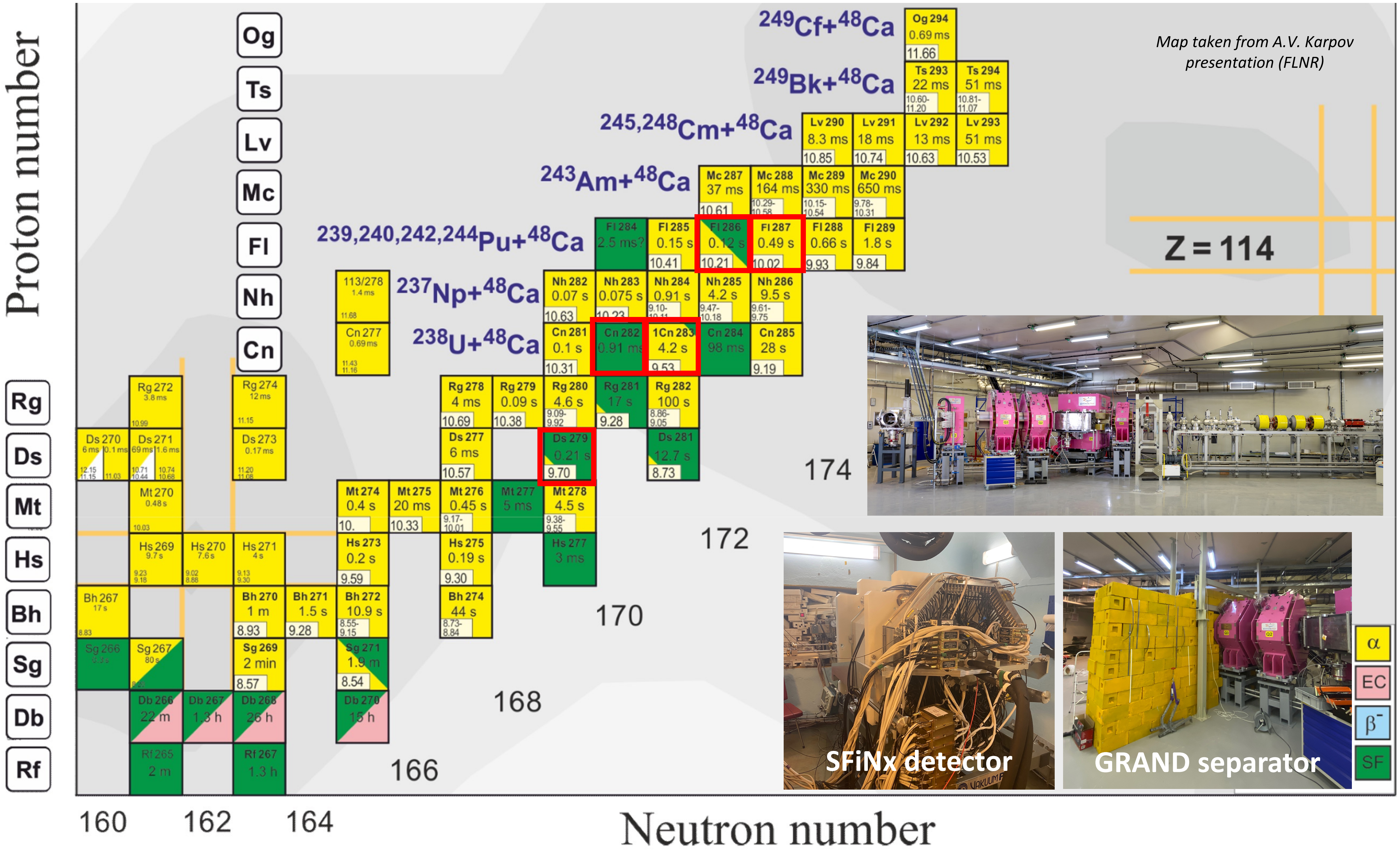
Nu-bar Value Systematic



Nu-bar Value Systematic



[Plans] Spontaneous Fission in the SHE region

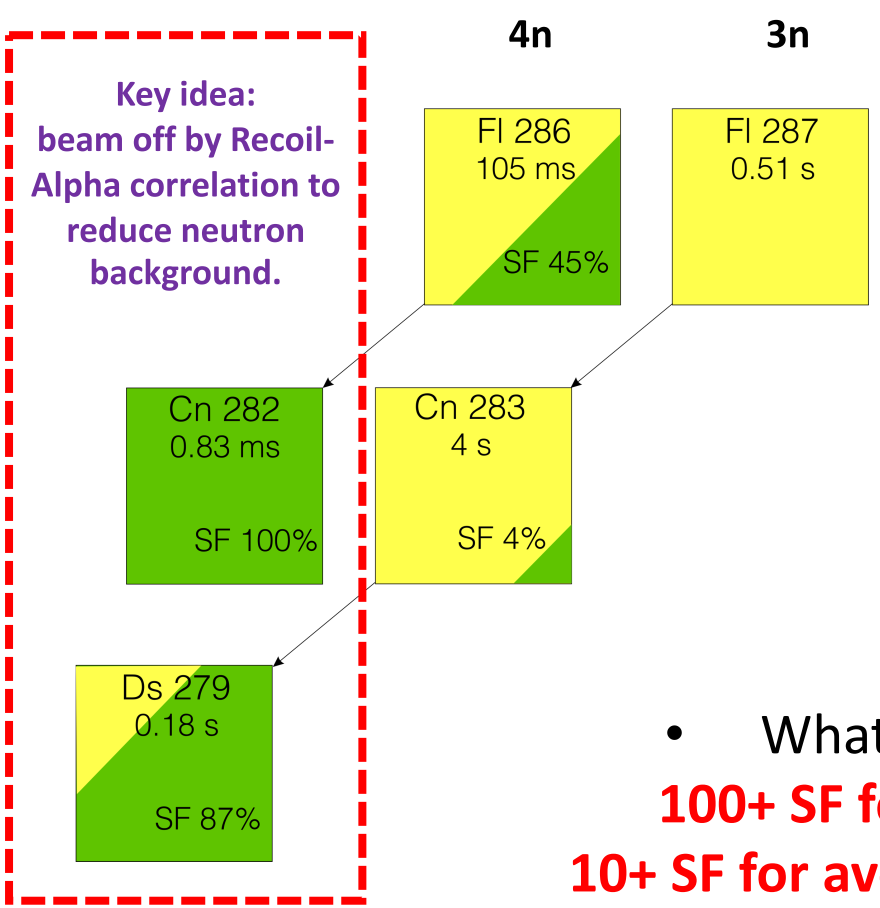


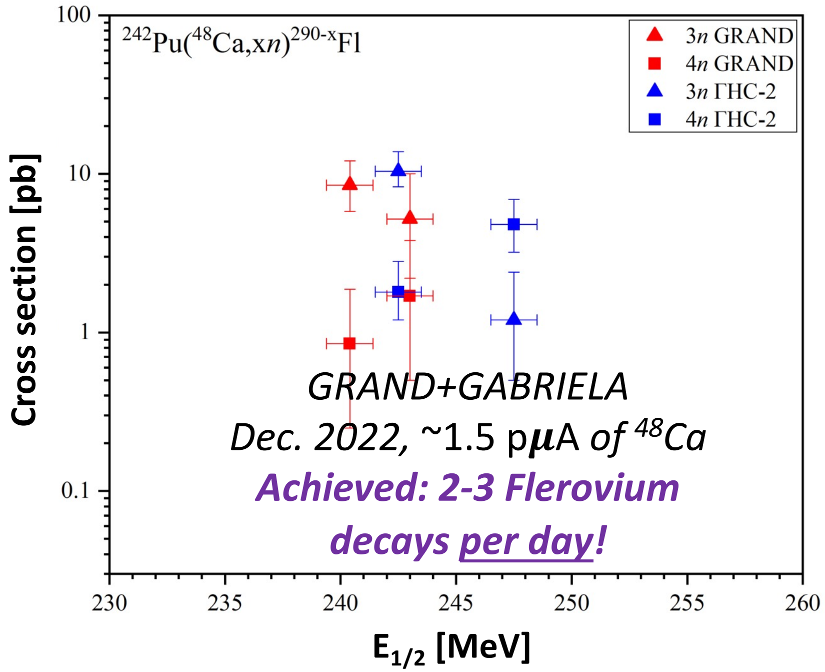
Map taken from A.V. Karpov presentation (FLNR)

[Plans] Spontaneous Fission in the SHE region

First tests of new rotating target
*D = 480 mm and **6?** pμA of ^{48}Ca*
SHE Factory, Apr. 2024
Plans for 2024: 1 Flerovium decay per hour!!

^{48}Ca + ^{242}Pu



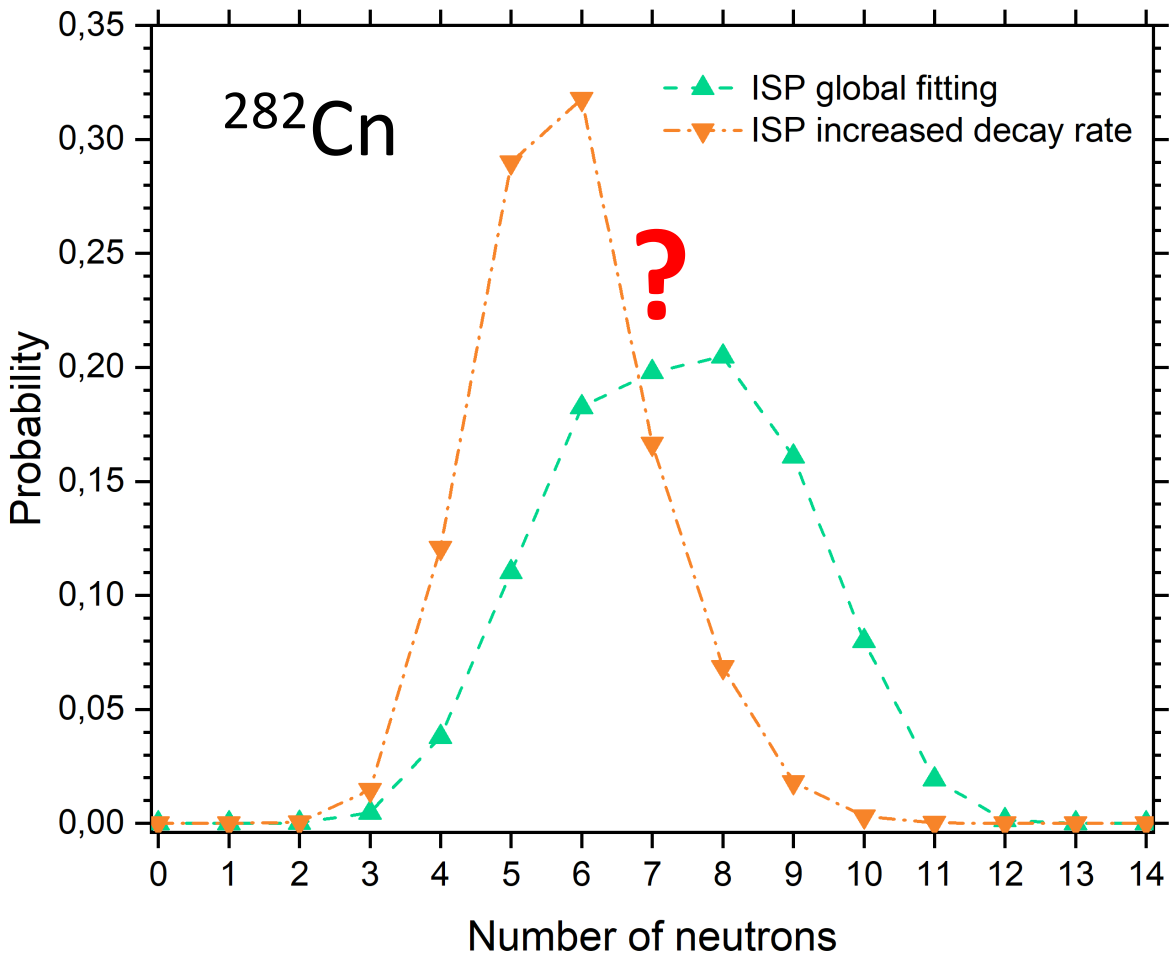


- What statistics are needed?

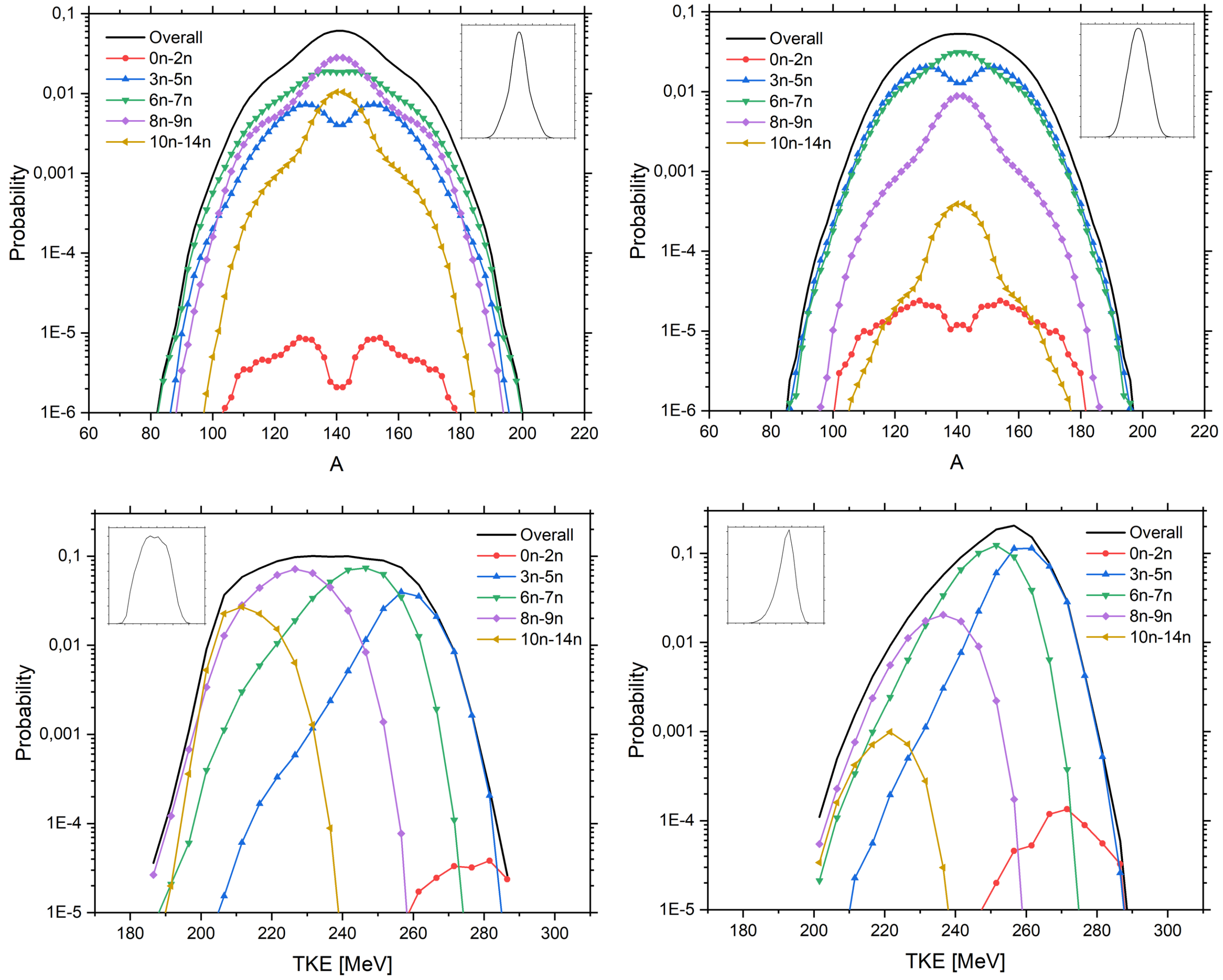
100+ SF for neutron multiplicity
10+ SF for average number of neutrons

- Several isotopes in the one experiment

[Plans] Spontaneous Fission in the SHE region



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

Conclusion

1. A highly efficient detection system SFiNx created for studying the SF of short-lived heavy nuclei
2. New data about prompt neutron emission obtained for few isotopes:

Isotope	Average number of *n* per SF act	Dispersion of distribution	Emission probabilities
^{244}Fm	3.5±0.2	1.4	substantially refined
^{246}Fm	3.8±0.3	2.1	substantially refined
^{250}No	**4.1±0.1**	**1.8**	**received for the first time**
^{252}No	4.25±0.09	2.1	substantially refined
^{260}Sg	**4.9±0.4**	**3.0**	**received for the first time**

3. The SFiNx will make it possible to advance research into the region of superheavy elements

Thank you for your attention!

III. Physics Instruments and Methods

First Prize

"The SFiNx detector system"
Authors: A. Isaev, R. Mukhin, A. Yeremin, A. Kuznetsova, O. Malyshev, A. Popeko, Yu. Popov, B. Sailaubekov, A. Svirikhin, E. Sokol