From cold fusion to hot fission

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Darmstadt, Germany

International conference "50 years of cold fusion"
Yerevan, Armenia
20-24 November 2024

Content

- Introduction
  - The cold-fusion reaction and its impact in the field
- Fission of heavy nuclei
  - The spontaneous-fission half-lives (even-even)
    - Experimental results with the focal plane detector @**TASCA**
  - The total kinetic energy and the mass distribution of fragments
    - Experimental results with the **ANSWERS**@**TASCA**
- Summary and conclusion

Superheavy elements: The cold-fusion (1975)

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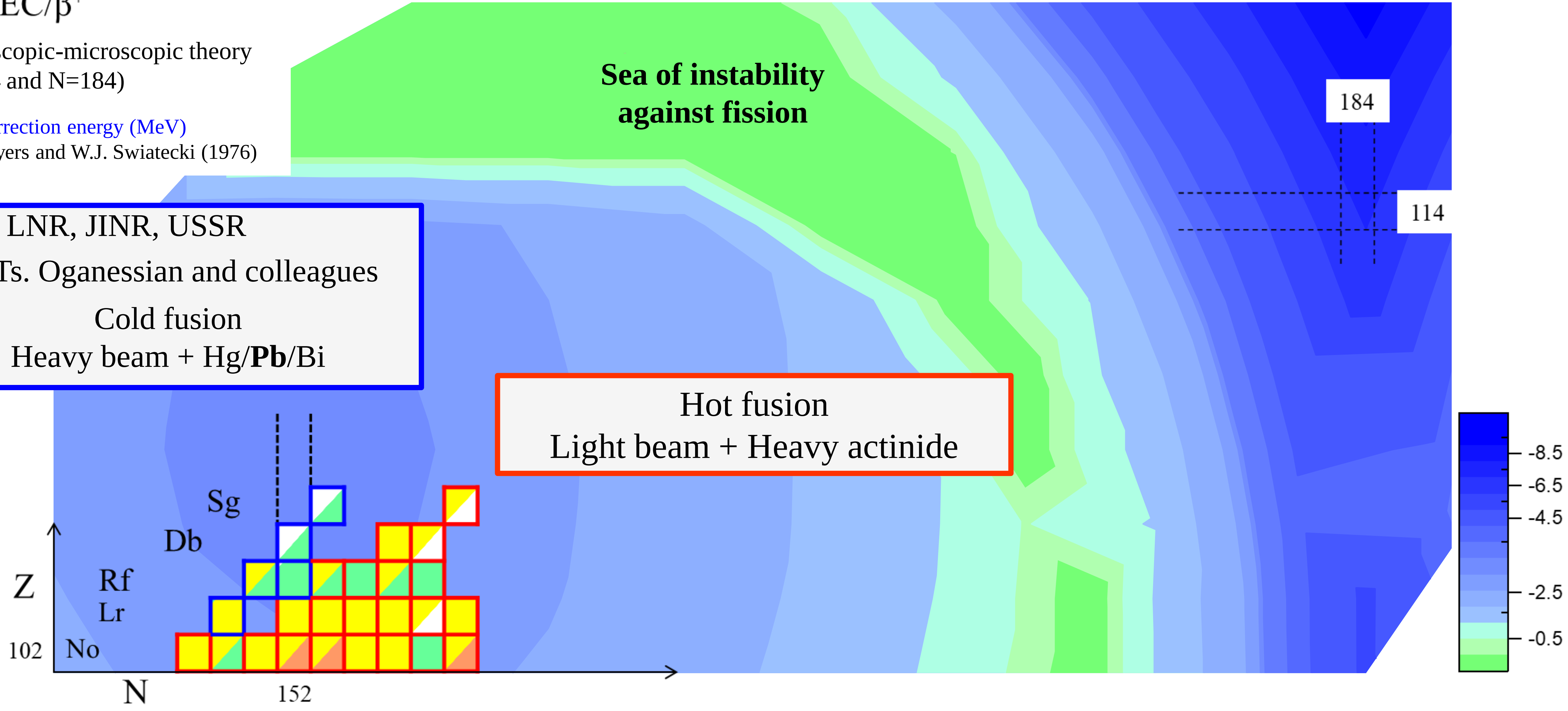
α Fission

EC/β+

Macroscopic-microscopic theory
(Z=114 and N=184)

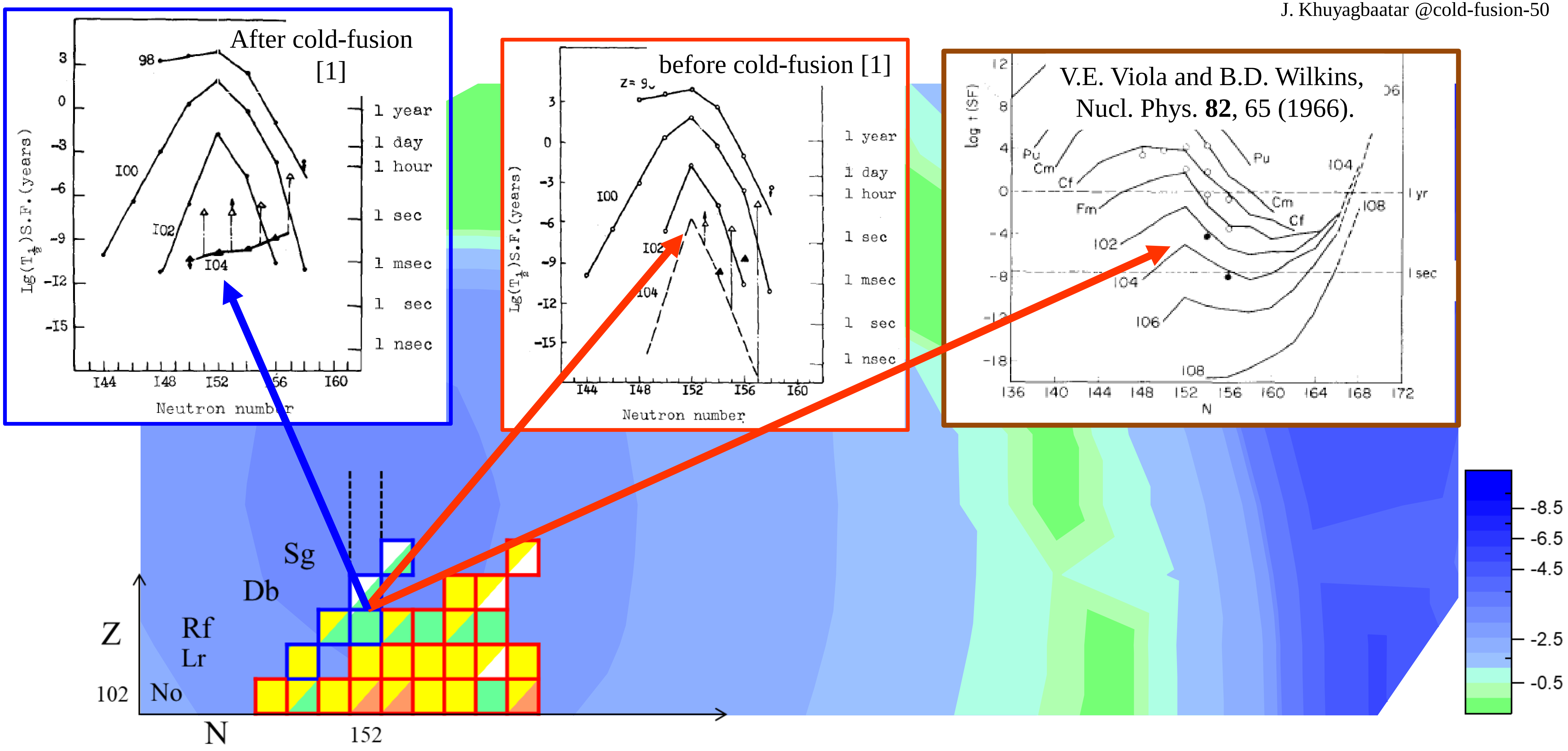
Shell correction energy (MeV)
W.D. Myers and W.J. Swiatecki (1976)

Island of stability
against fission



[1] Yu.Ts. Oganessian, Lect. Notes. Phys. 33, 221 (1975).
[2] M. Nurmia et al., Phys. Lett. 26B, 78 (1967).

The cold-fusion: Unexpectedly short-lived fission of ^{256}Rf



[1] Yu.Ts. Oganessian, Lect. Notes. Phys. 33, 221 (1975).

The fission-barrier shape of superheavy nuclei

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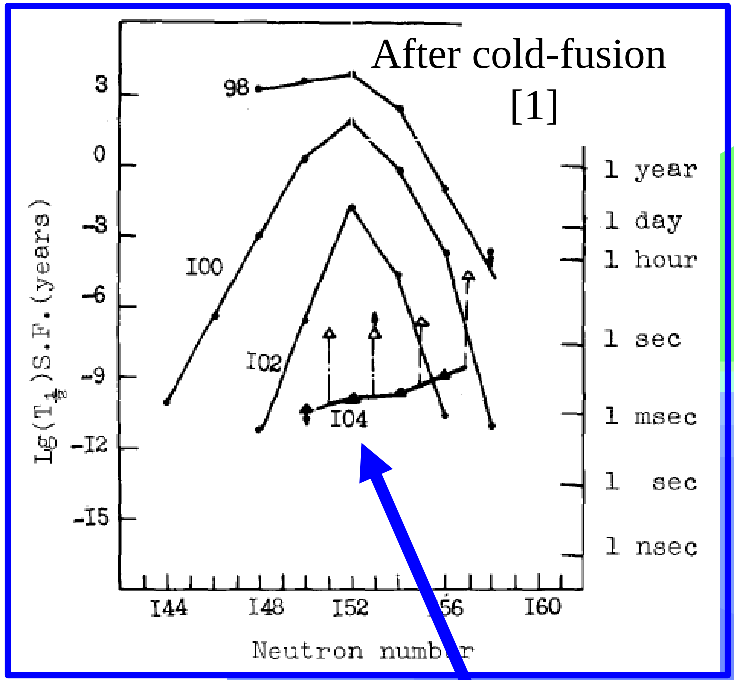
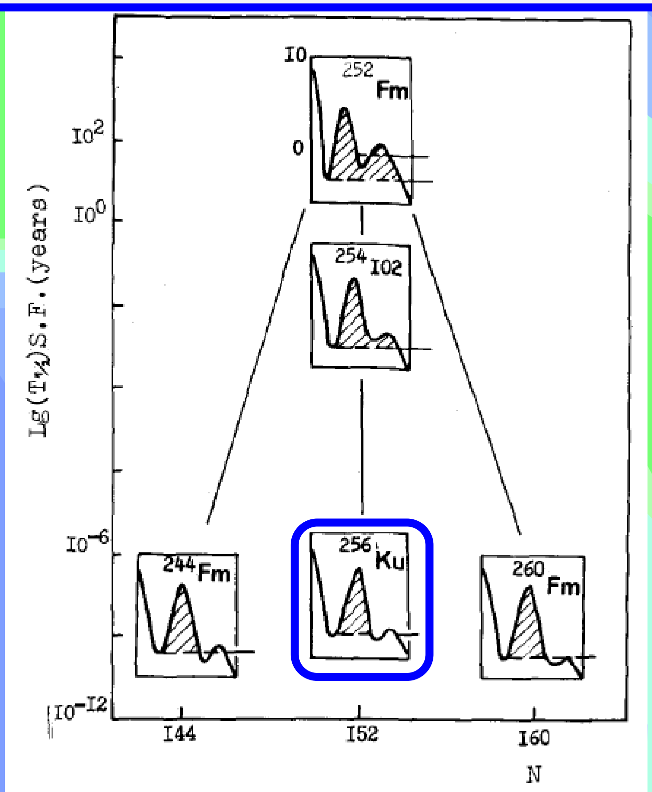
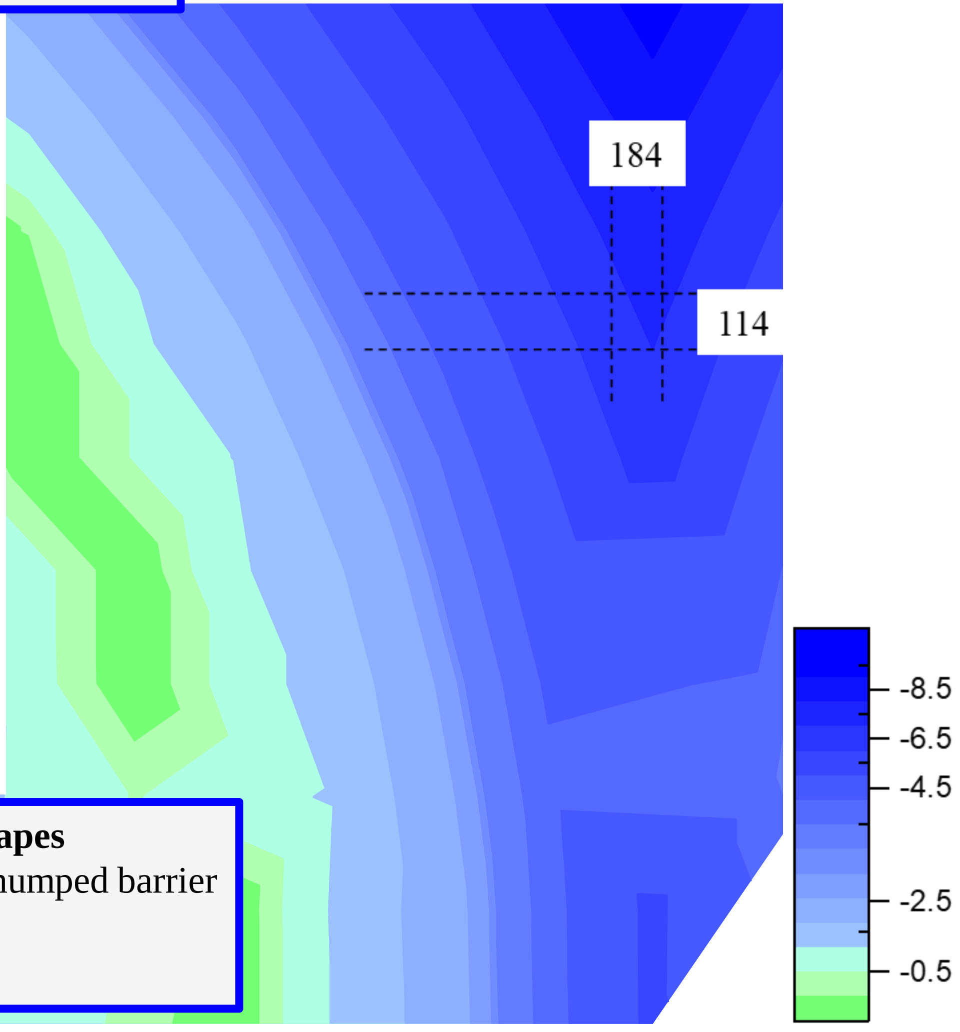
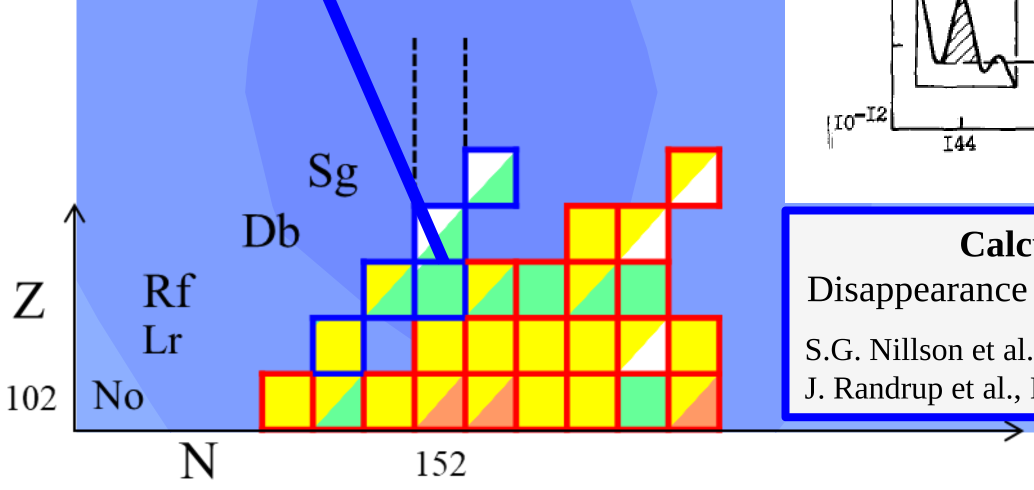


Doubled-humped fission barrier (V.M. Strutinsky 1967)
Disappearance of outer barrier in ^{256}Rf [1]







Calculated fission-barrier shapes
Disappearance of outer barrier ~ Single-humped barrier

S.G. Nillson et al., Nucl. Phys. A **131**, 1 (1969)
J. Randrup et al., Nucl. Phys. A 217, 221 (1973)

[1] Yu.Ts. Oganessian, Lect. Notes. Phys. 33, 221 (1975).

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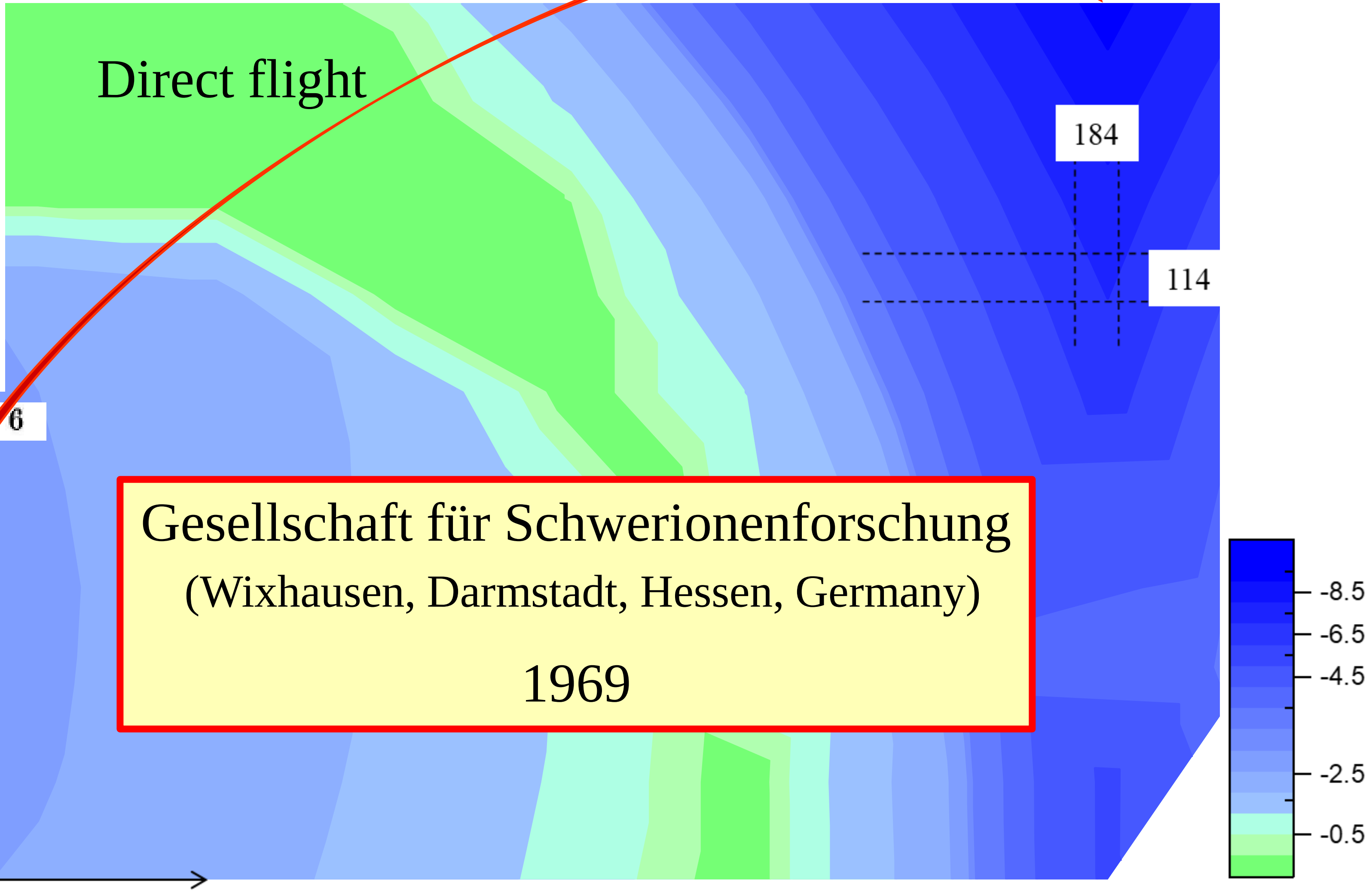
Sikkeland: tens of mb's cross-sections for element 126

Table 1. Analysis of calculated excitation functions for the production of the nuclides $^{312-x}126$ and $^{200-x}Po$.

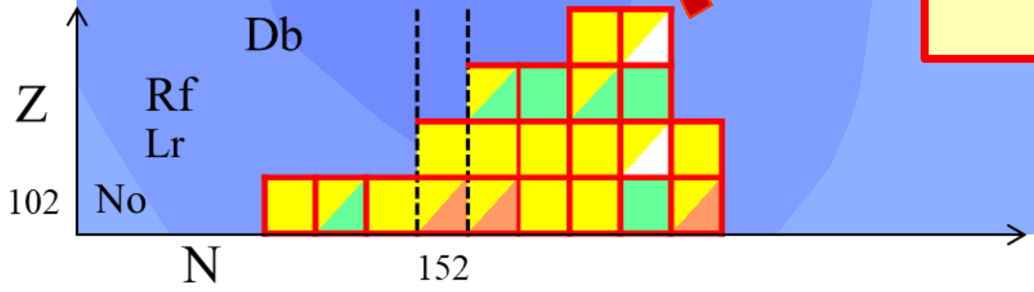
System	Spallation product	Peak cross section (mb) I[a]	Peak cross section (mb) II[b]	Ion energy (MeV/nucleon) I[a]	Ion energy (MeV/nucleon) II[b]	FWHM (MeV) I[a]	FWHM (MeV) II[b]
$^{180}Hf + ^{132}Xe$	$^{312}126$	73	73	5.27	5.27	—	—
	$^{311}126$	92	93	5.39	5.36	19	20
	$^{310}126$	111	115	5.55	5.50	26	20
	$^{309}126$	103	127	5.72	5.63	30	19
	$^{308}126$	77	98	5.89	5.77	35	20
$^{232}Th + ^{80}Kr$	$^{311}126$	.02	.02	5.44	5.44	9	8
	$^{310}126$	12	11	5.49	5.48	10	8
	$^{309}126$	55	48	5.63	5.61	15	14
	$^{308}126$	67	62	5.85	5.76	20	17
$^{252}Cf + ^{60}Ni$	$^{311}126$	.0004	.0004	5.72	5.73	—	—
	$^{310}126$	.5	.4	5.77	5.75	8	8
	$^{309}126$	22	20	5.83	5.82	12	10
	$^{308}126$	59	52	6.05	6.00	18	15

Proc. of the Lysekil Symposium, 1966 · Session IX, No 6

Excitement



Gesellschaft für Schwerionenforschung
(Wixhausen, Darmstadt, Hessen, Germany)
1969



Superheavy elements @Gesellschaft für Schwerionenforschung: 1970s

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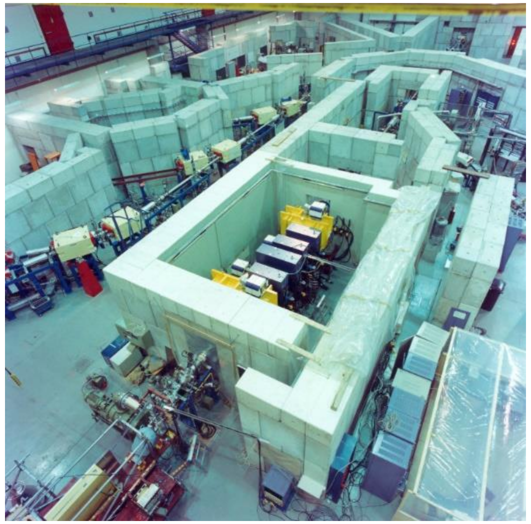
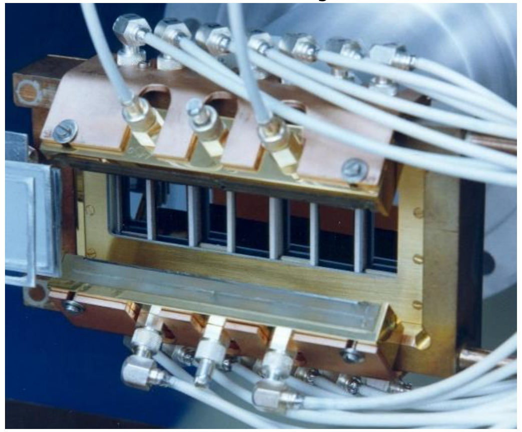
The state-of-the-art instruments

UNILAC (Heavy-ion beam)

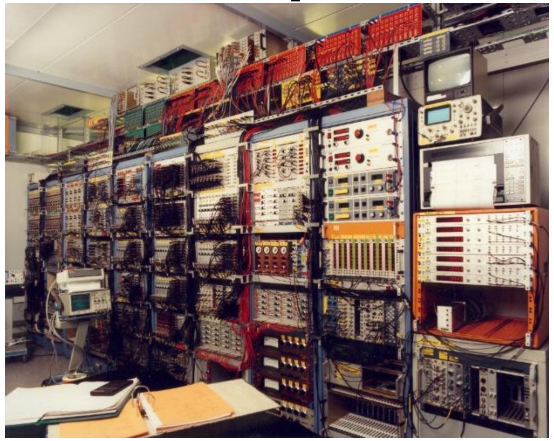
SHIP (Separator)

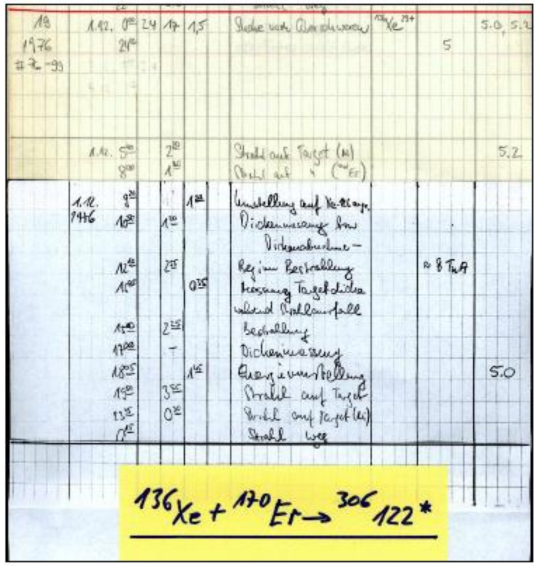


Detection system



Data acquisition





4×4 h, $\sigma < 1$ nb

First, second ... attempts
Disappointment

Figures provided by S. Hofmann

Nuclear reaction dynamics @GSI

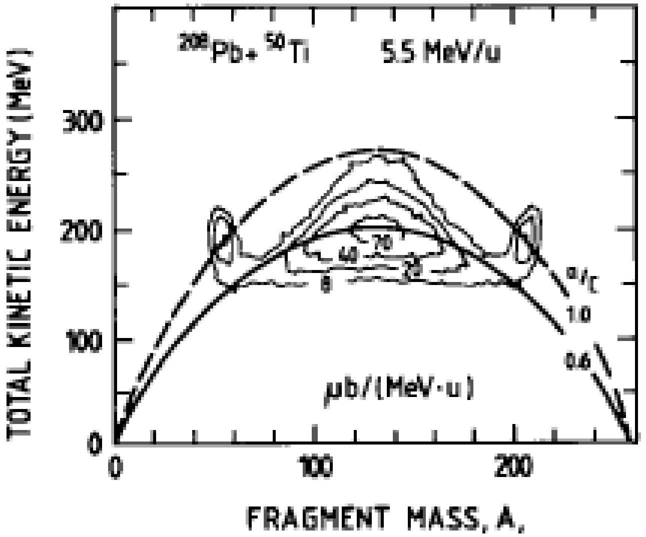
R. Bock et al., Nucl. Phys. A 388, 334 (1982)

Mass-Energy Distribution
Mass-Angle Distribution

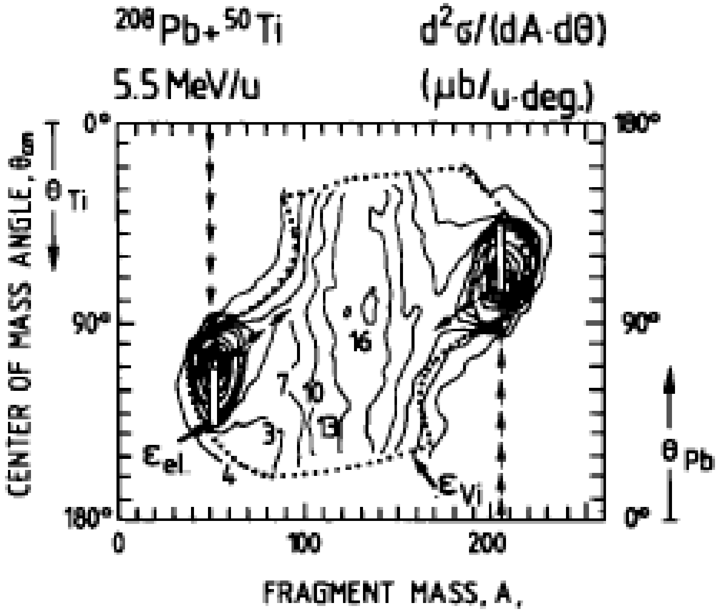
J. Toke et al., Nucl. Phys. A 440, 327 (1985)
W.Q. Shen, et al., Phys. Rev. C **36**, 115 (1987)
…

Quasi-fission
Inverse kinetics
…

Mass-Energy Distribution (MED)



Mass-Angle Distribution (MAD)



Non-observations of 121 and 122 elements were explained.

$^{65}Cu + ^{238}U \rightarrow ^{303}121^*$

$^{136}Xe + ^{170}Er \rightarrow ^{306}122^*$

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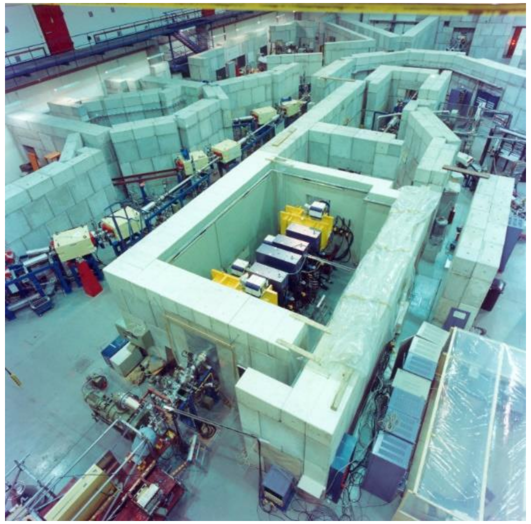
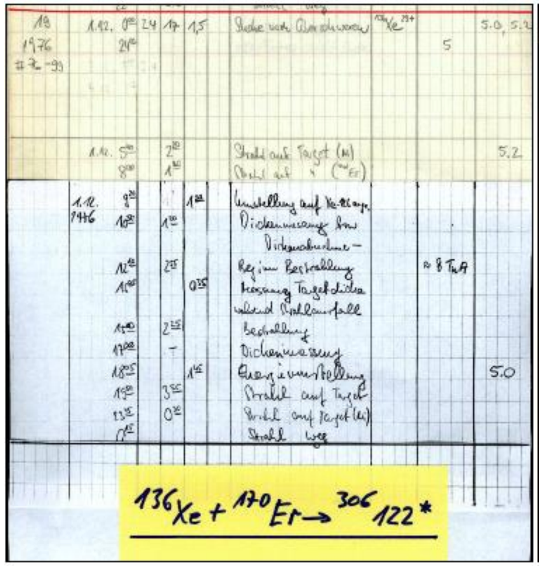
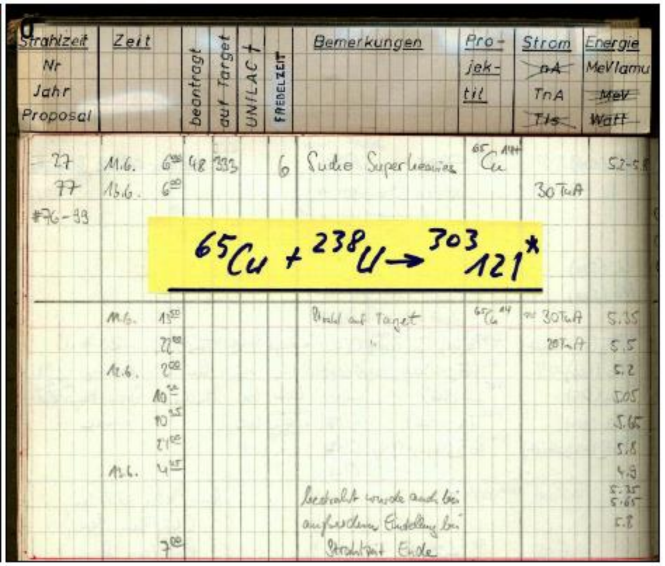
The state-of-the-art instruments

UNILAC (Heavy-ion beam)

SHIP (Separator)



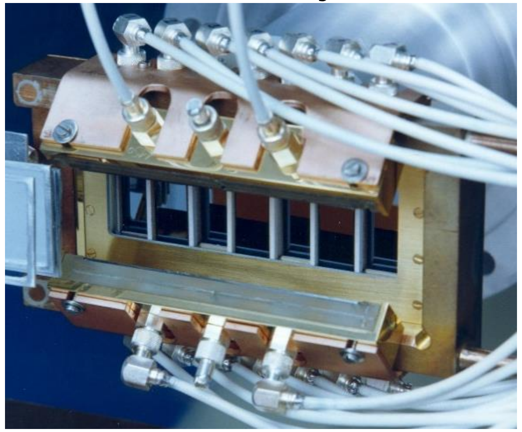




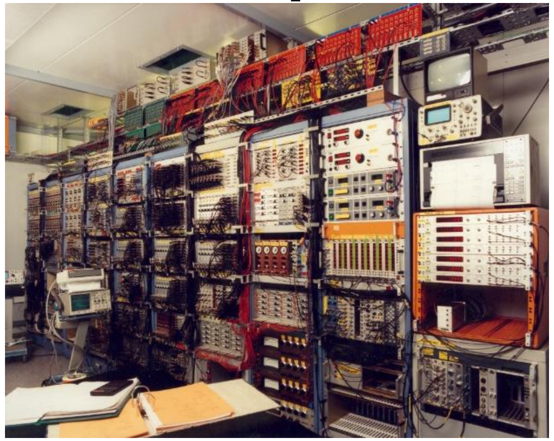
4×4 h, σ < 1 nb

7×6 h, σ < 0.4 nb

Detection system



Data acquisition



Nothing was wrong with instruments/experiment

Yu.Ts. Oganessian and colleagues

Cold fusion

Heavy beam + Hg/**Pb**/Bi

Figures provided by S. Hofmann

The state-of-the-art focal plane implantation/correlation technique @SHIP

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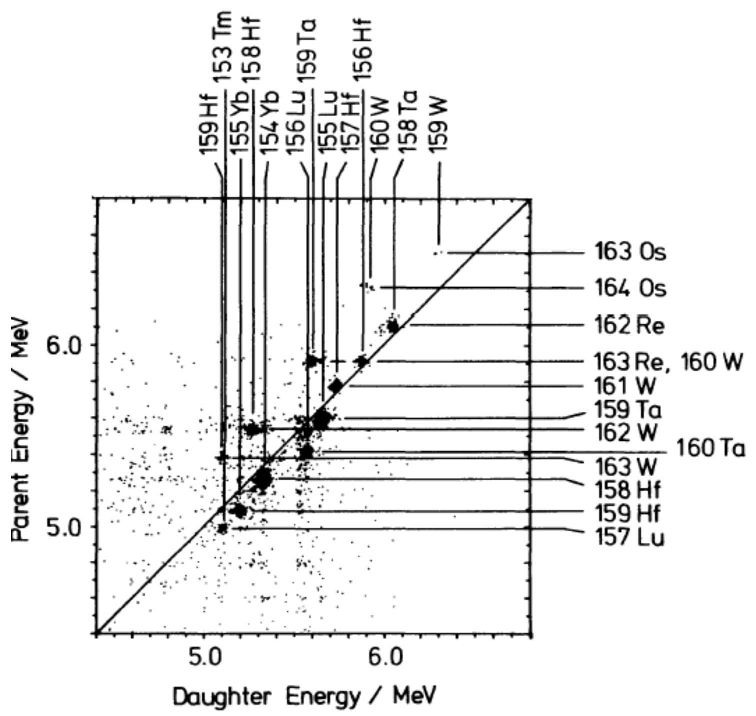
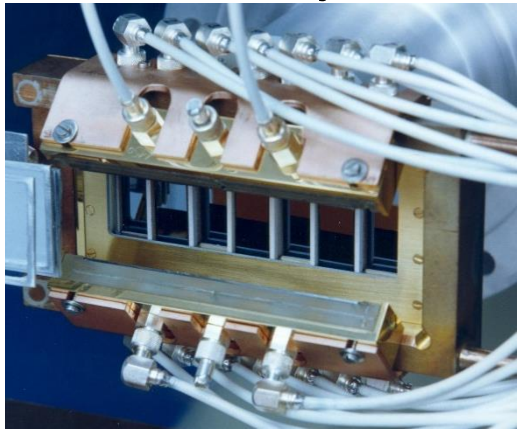
1977
S. Hofmann, W. Faust, G. Münzenberg, W. Reisdorf, P. Armsbruster, K. Guttner and H. Eward, Z. Phys. A **291**, 53 (1979).

S. Hofmann, G. Münzenberg, F.P. Heβberger and H.J. Schott, NIM A **223**, 312 (1984).

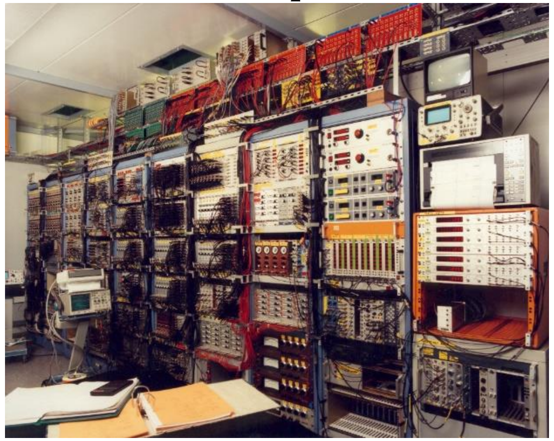
11 new isotopes were discovered in a single experiment!



Detection system



Data acquisition



1981: Element 107 (Bohrium)
1982: Element 109 (Meitnerium)
1982: Proton radioactivity
1984: Element 108 (Hassium)
1994: Element 110 (Darmstadtium)
1994: Element 111 (Röntgenium)
1996: Element 112 (Copernicium)
…many more …

Figures provided by S. Hofmann

The cold-fusion @SHIP: The new shell gap

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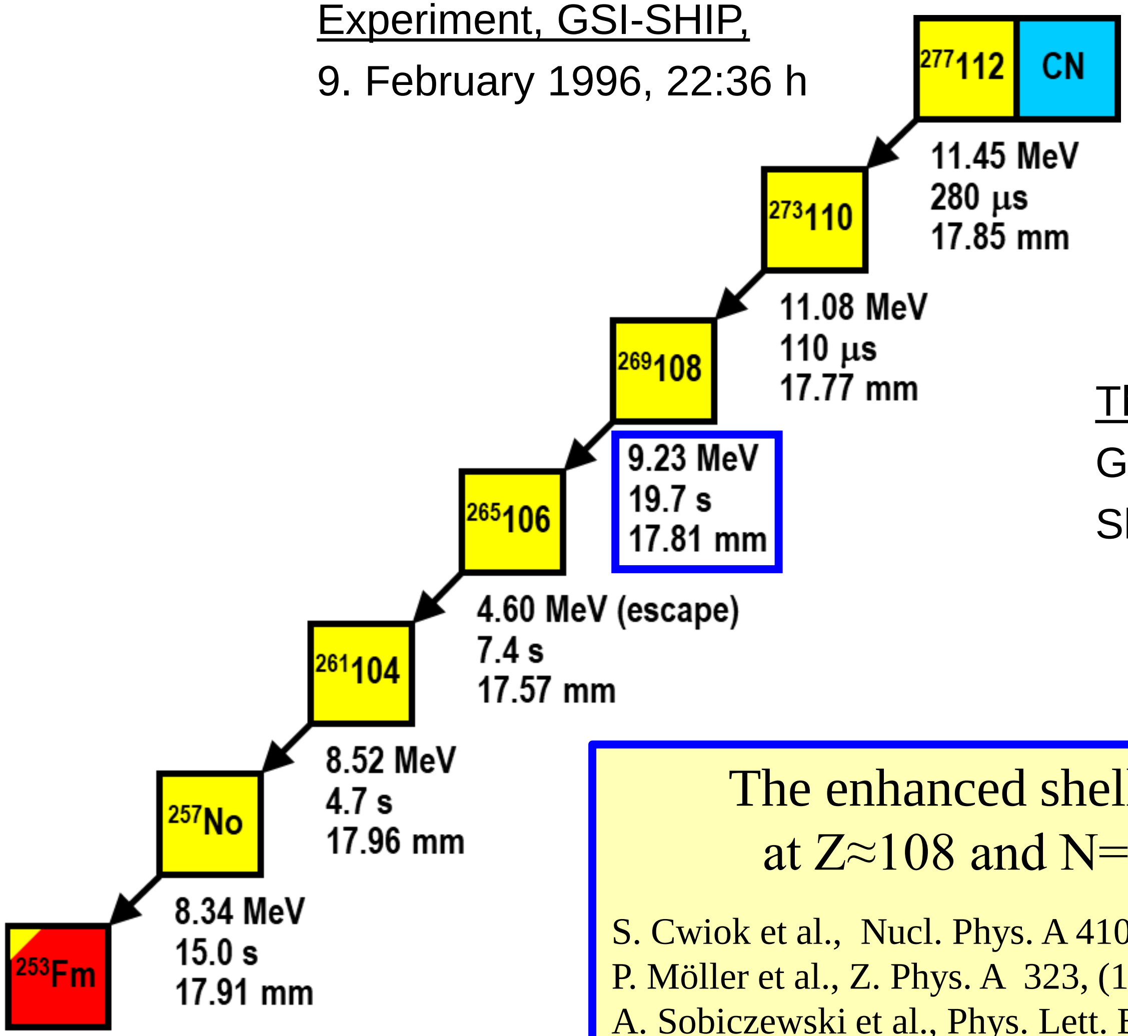
Experiment, GSI-SHIP,

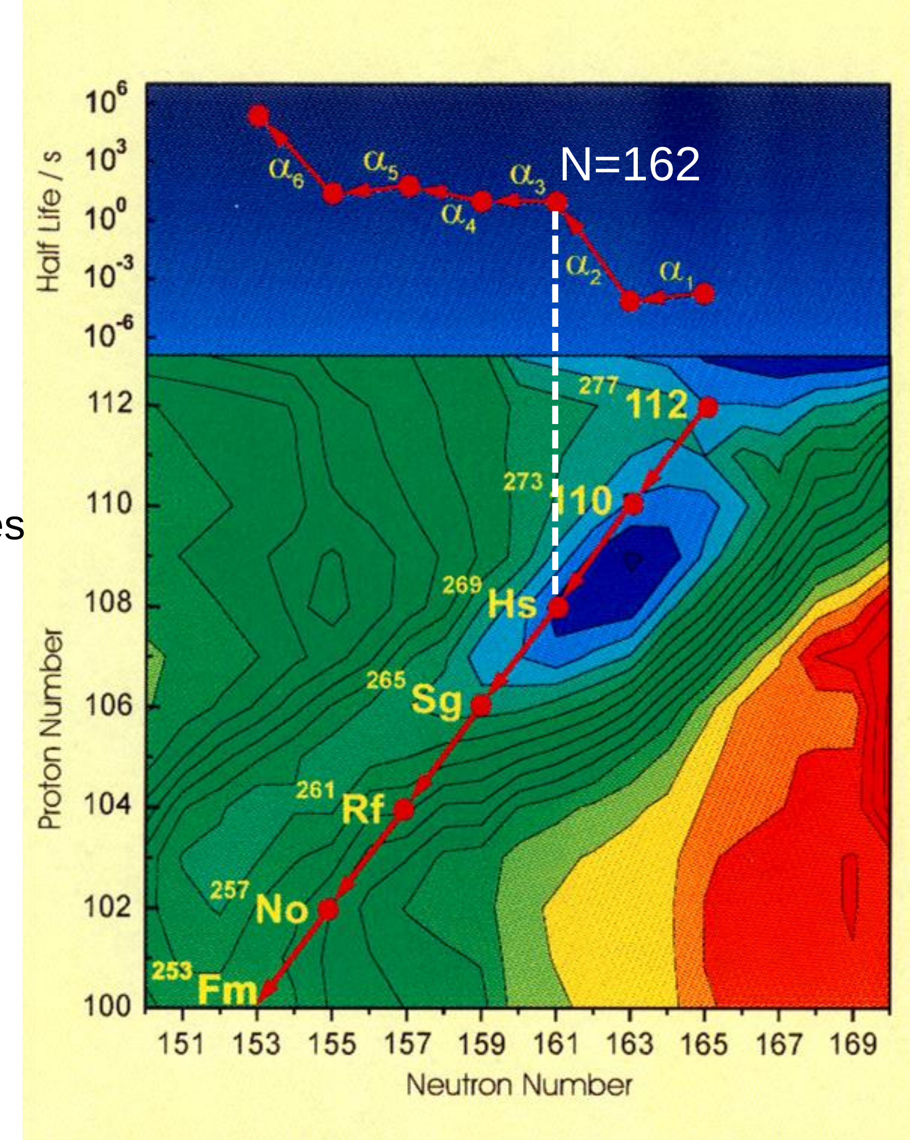
9. February 1996, 22:36 h



Theory, P. Möller, 1995:

Ground-state

Shell-correction energies



The enhanced shell gap
at Z≈108 and N=162

S. Cwiok et al., Nucl. Phys. A 410, 254 (1983)
P. Möller et al., Z. Phys. A 323, (1986)
A. Sobiczewski et al., Phys. Lett. B **186**, 6 (1987)

Island of stability

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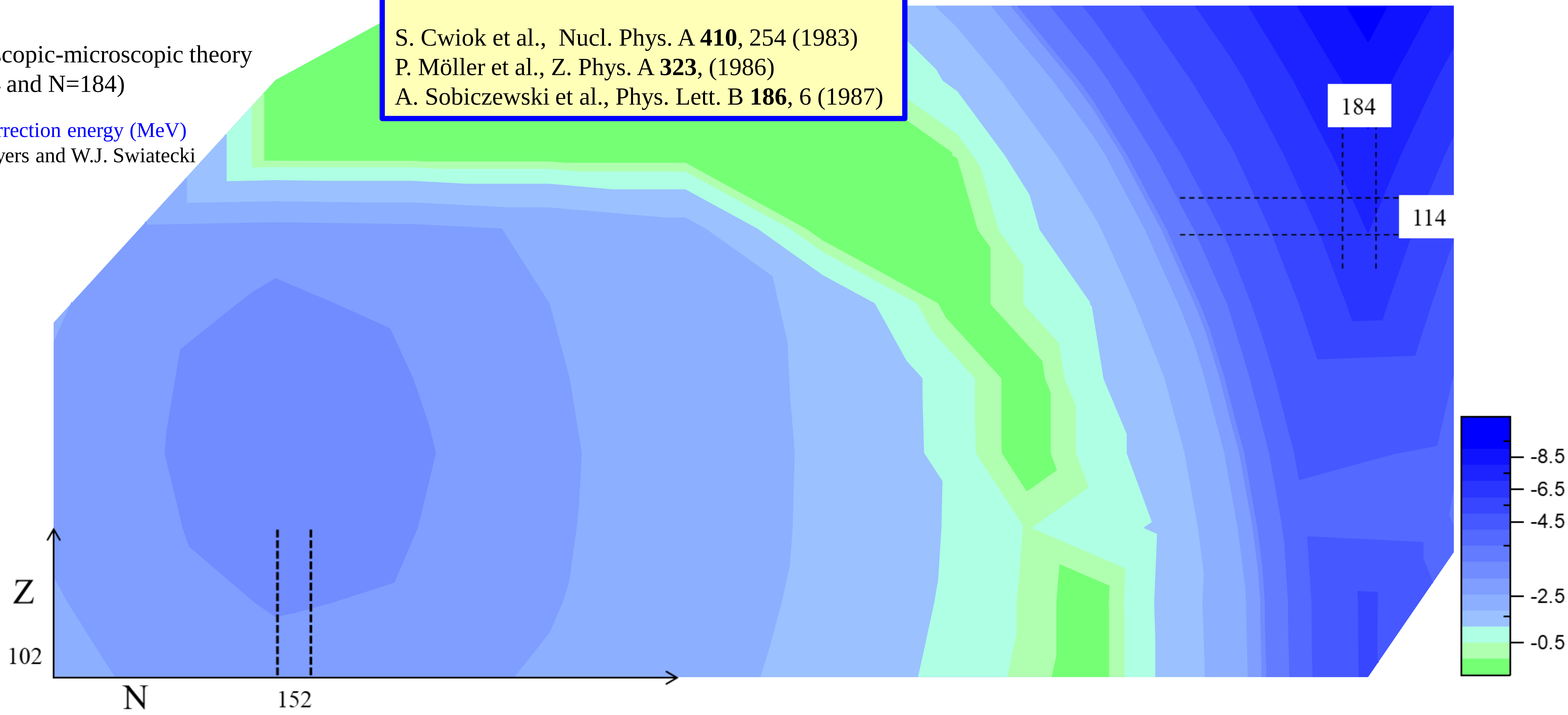
The enhanced shell gap at Z≈108 and N=162

S. Cwiok et al., Nucl. Phys. A **410**, 254 (1983)
P. Möller et al., Z. Phys. A **323**, (1986)
A. Sobiczewski et al., Phys. Lett. B **186**, 6 (1987)

Macroscopic-microscopic theory (Z=114 and N=184)

Shell correction energy (MeV)
W.D. Myers and W.J. Swiatecki



Fission-landscape of superheavy nuclei

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The enhanced shell gap
at Z≈108 and N=162

S. Cwiok et al., Nucl. Phys. A **410**, 254 (1983)
P. Möller et al., Z. Phys. A **323**, (1986)
A. Sobiczewski et al., Phys. Lett. B **186**, 6 (1987)

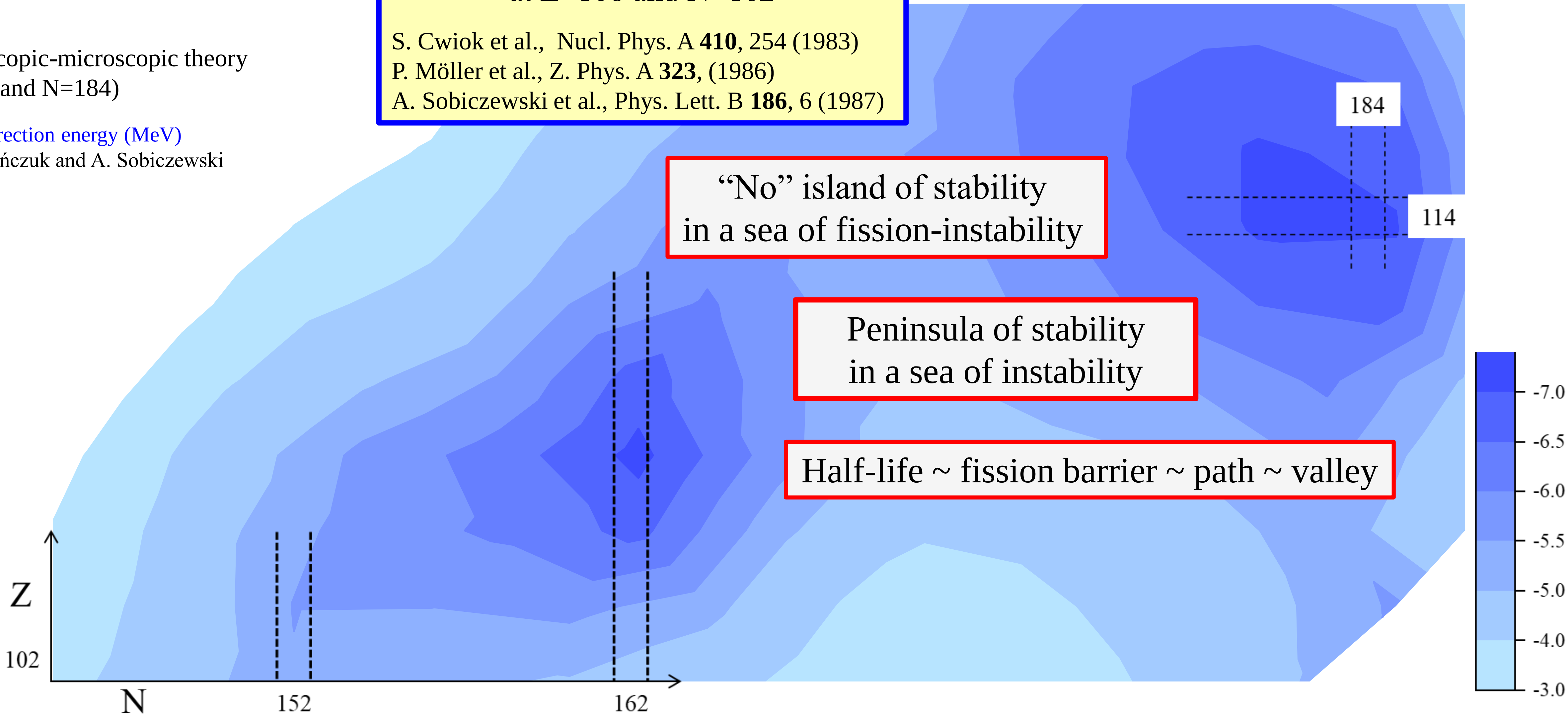
Macroscopic-microscopic theory
(Z=114 and N=184)

Shell correction energy (MeV)
R. Smolańczuk and A. Sobiczewski

“No” island of stability
in a sea of fission-instability

Peninsula of stability
in a sea of instability

Half-life ~ fission barrier ~ path ~ valley



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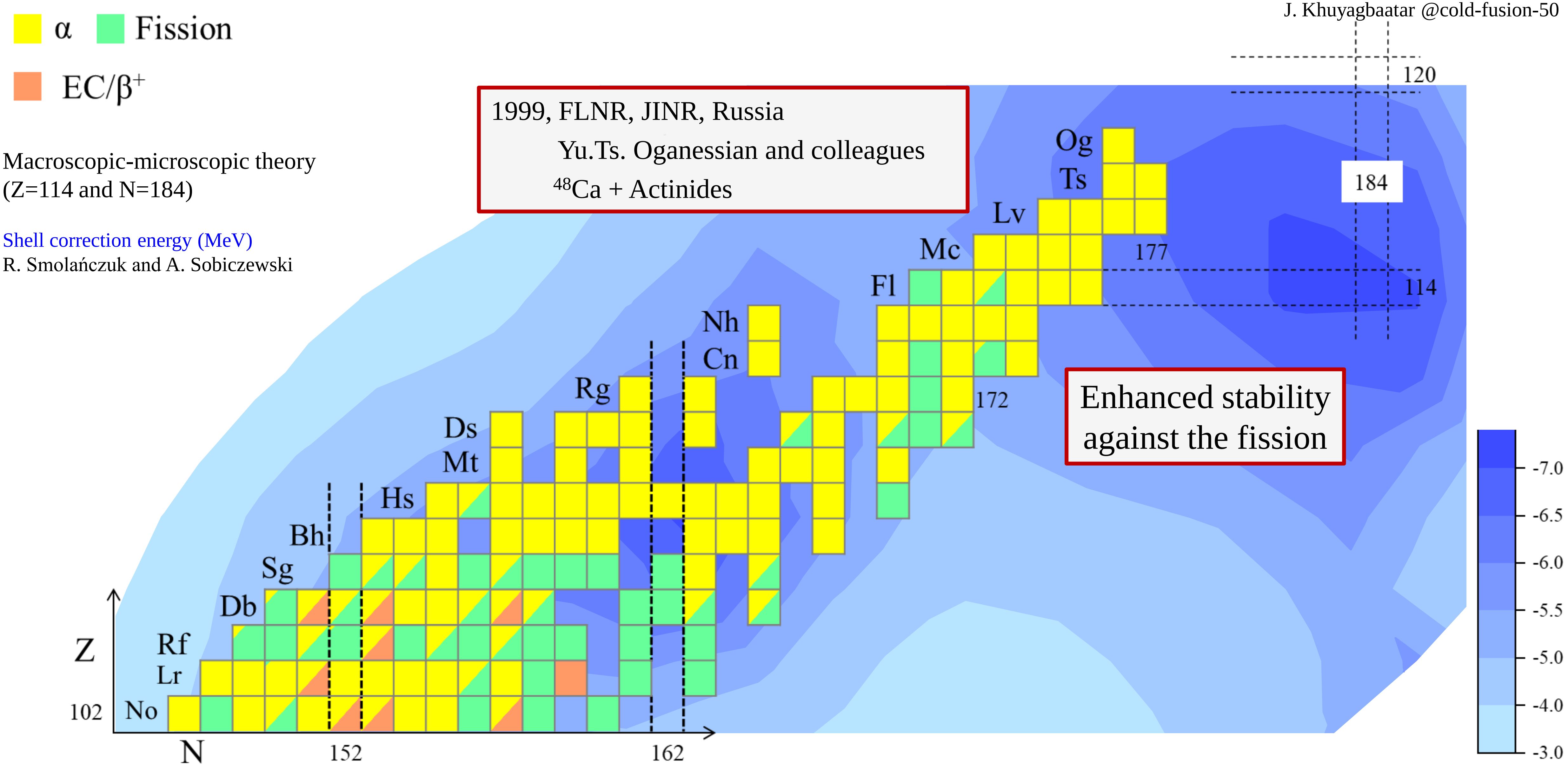
1999, FLNR, JINR, Russia

Yu.Ts. Oganessian and colleagues

^{48}Ca + Actinides

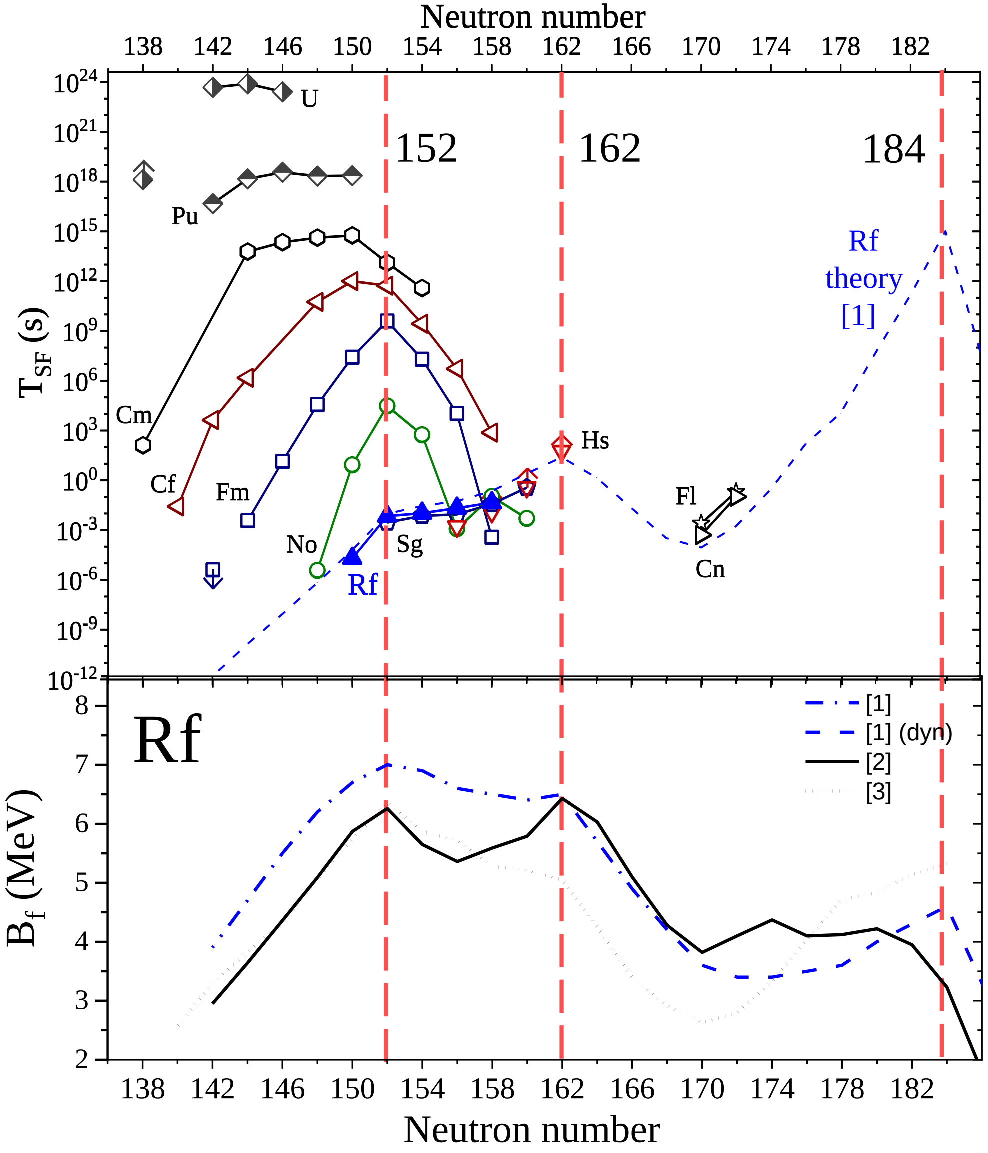
Macroscopic-microscopic theory (Z=114 and N=184)

Shell correction energy (MeV)
R. Smolańczuk and A. Sobiczewski



Enhanced stability against the fission

Fission half-life and fission barrier



J. Khuyagbaatar et al., EPJ Web Conf. **131**, 03003 (2016).

Experiment
T_{SF} of even-even isotopes define the fission-landscape

"Semi-empirical" systematics
T_{SF} (exp) ~ B_f(theory)

V.E. Viola and B.D. Wilkins, Nucl. Phys. **82**, 65 (1966).

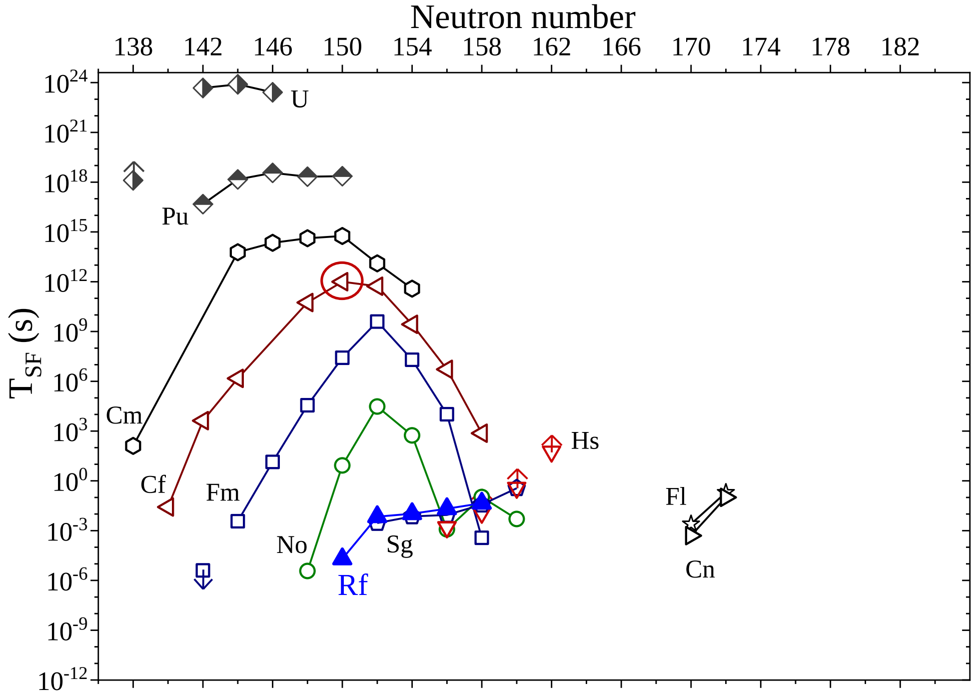
Shape of the fission barrier ?

F. P. Heßberger et al., J. Less. Com. Met. **122**, 445 (1986).

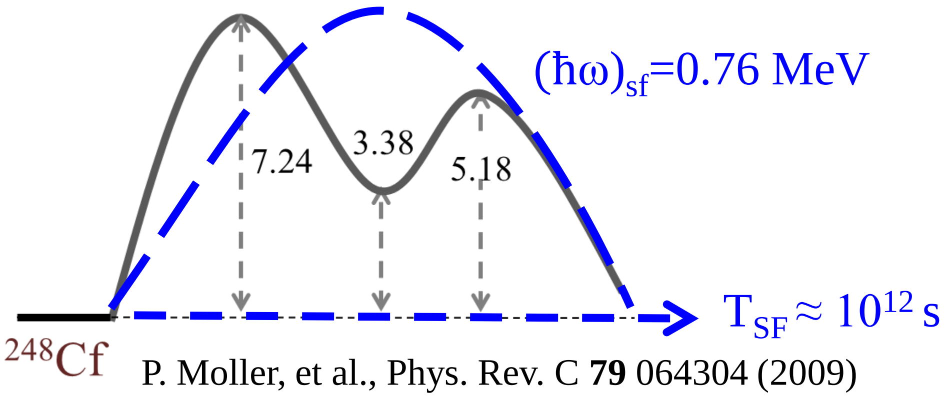
Theory
B_f (Height): Global variable
Shape: Local variable

Extremely challenging problems

[1] R. Smolańczuk, J, Skalski and A. Sobiczewski, Phys. Rev.C **52** 1871 (1995)
[2] P. Möller, et al., Phys. Rev. C **79** 064304 (2009)
[3] M. Kowal, P. Jachimowicz, and A. Sobiczewski, Phys. Rev. C **82** 014303 (2010)



J. Khuyagbaatar, Nucl. Phys. A **1002**, 121958 (2020).



P. Moller, et al., Phys. Rev. C **79** 064304 (2009)

Fission probability (parabolic-shaped barrier)

D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).

$$T \approx \left[1 + \exp\left(\frac{2\pi(B_f - E)}{\hbar\omega_f}\right)\right]^{-1}$$

Semi-empirical approach: Ground-state fission-barrier shapes of SHN

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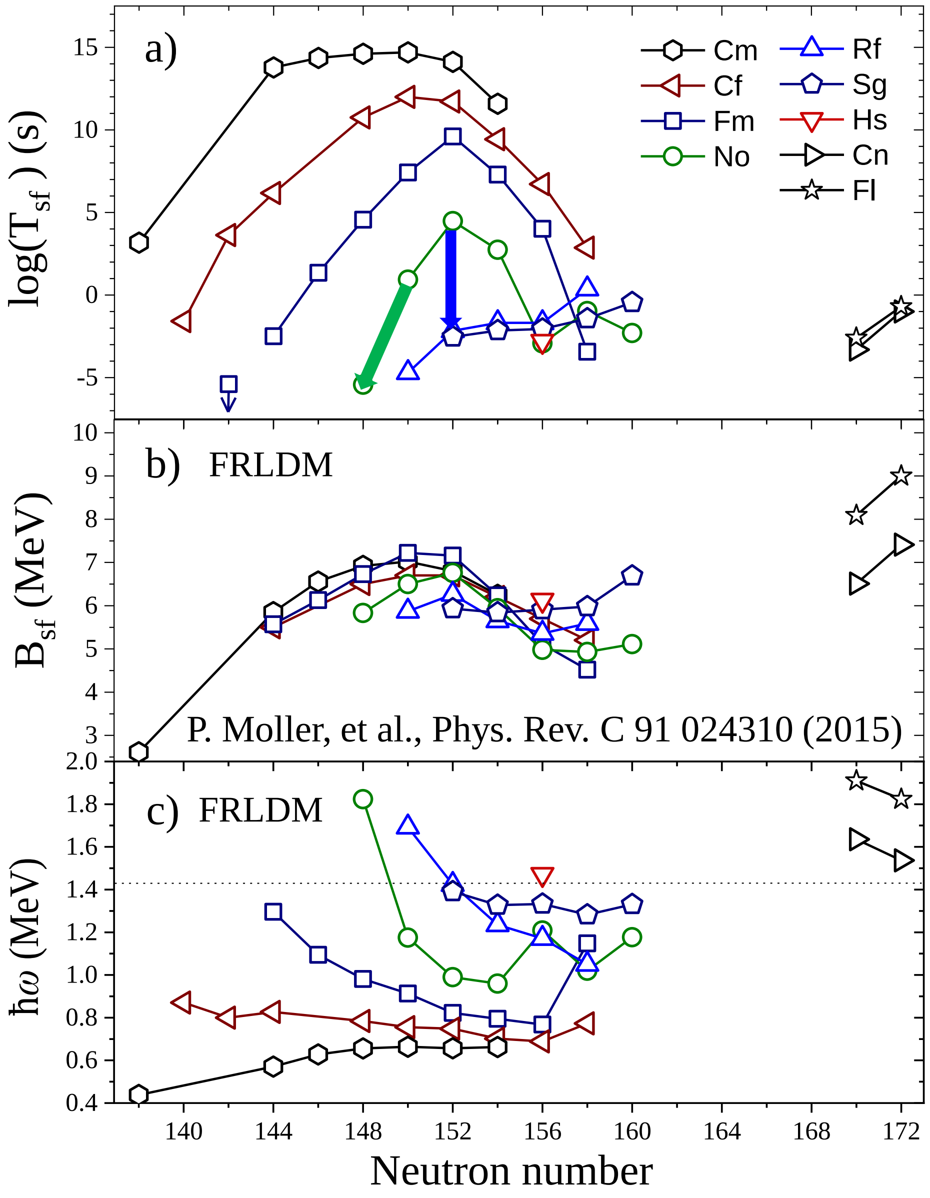
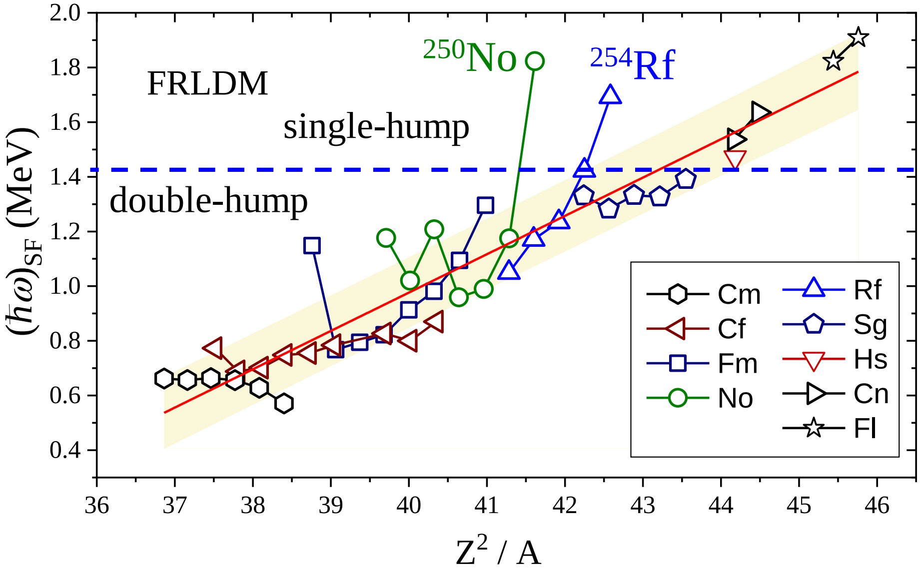


J. Khuyagbaatar, Nucl. Phys. A **1002**, 121958 (2020).



No outer barrier in ^{256}Rf

Yu.Ts. Oganessian et al., Nucl. Phys. A **239**, 157 (1975).

SHN

Narrow-shaped fission barrier !

Shorter fission half-lives ?

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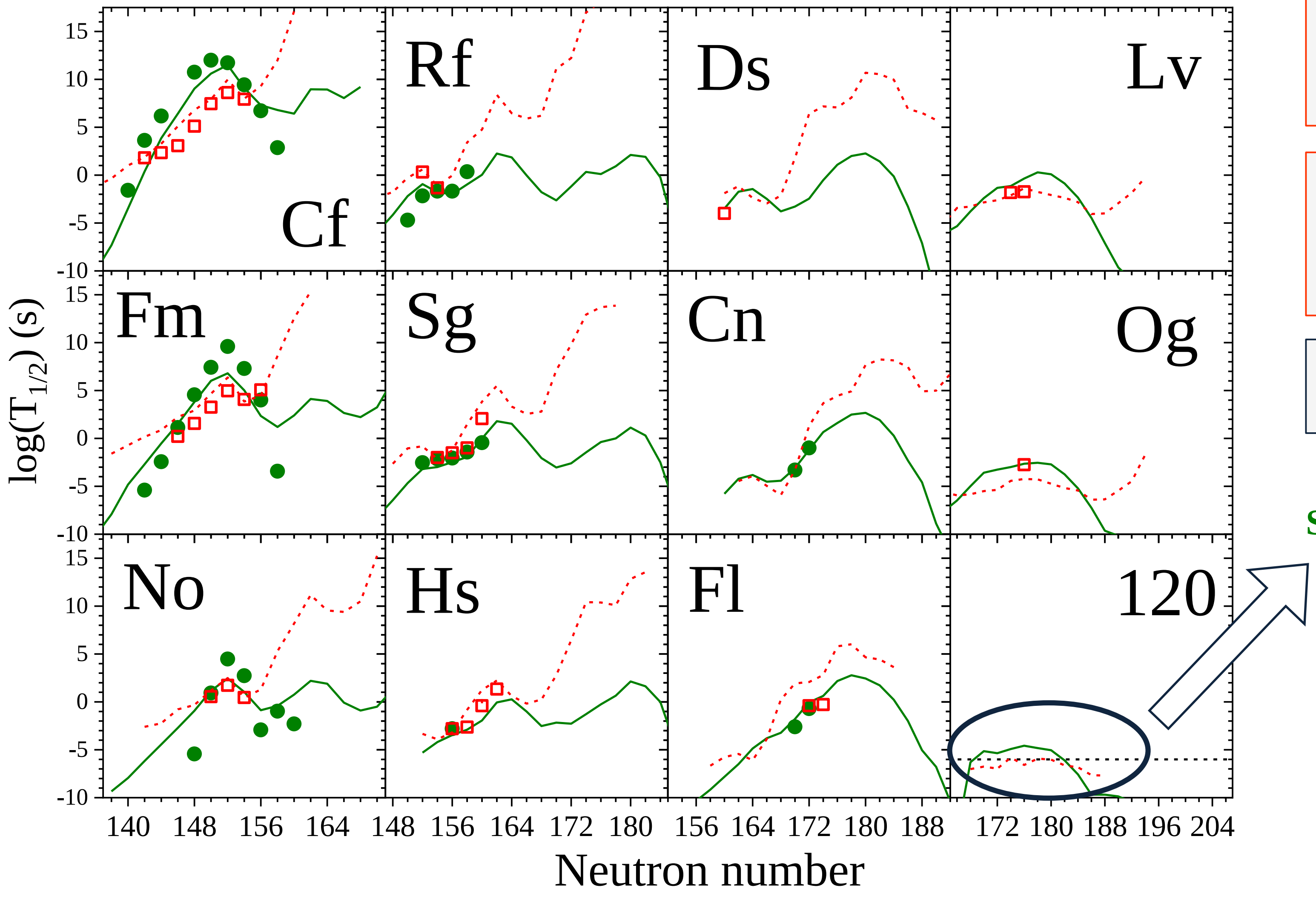
J. Khuyagbaatar, Nucl. Phys. A **1002**, 121958 (2020).

T_{SF}: Semi-empirical estimates with B_f from P. Möller, et al., Phys. Rev. C 91 (2015) 024310.
T_α: from P. Möller, et al., At. Data Nucl. Data Tables 66 (1997) 131.



SHE-Factory, FLNR, JINR
Yu.Ts. Oganessian *et al.*, Phys. Rev. C **108**, 024611 (2023)

^{276}Ds: $T_{SF} \approx 0.27^{+0.23}_{-0.10}$ ms — T_{SF} (est.) ≈ 3 ms
^{268}Sg: $T_{SF} \approx 13^{+17}_{-4}$ s — T_{SF} (est.) ≈ 62 s

TASCA, GSI
A. Samark-Roth et al., Phys. Rev. Lett. **126,** 032503 (2021)

^{280}Ds: $T_{SF} \approx 0.36^{+1.72}_{-0.18}$ ms — T_{SF} (est.) ≈ 0.5 ms

R-process calculation: WinNet
M. Reichert *et al* 2023 *Astrophysical J.S.* **268** 66 (2023)

Spontaneous fission from even-even isotopes of 120 element is not excluded!

Peninsula of stability
in the
sea of instability ($<10^{-14}$ s) - **?**

Island of increased stability
(in comparison with neighboring nuclei)
O. R. Smits et al., Nat. Rev. Phys. **6**, 86 (2024).

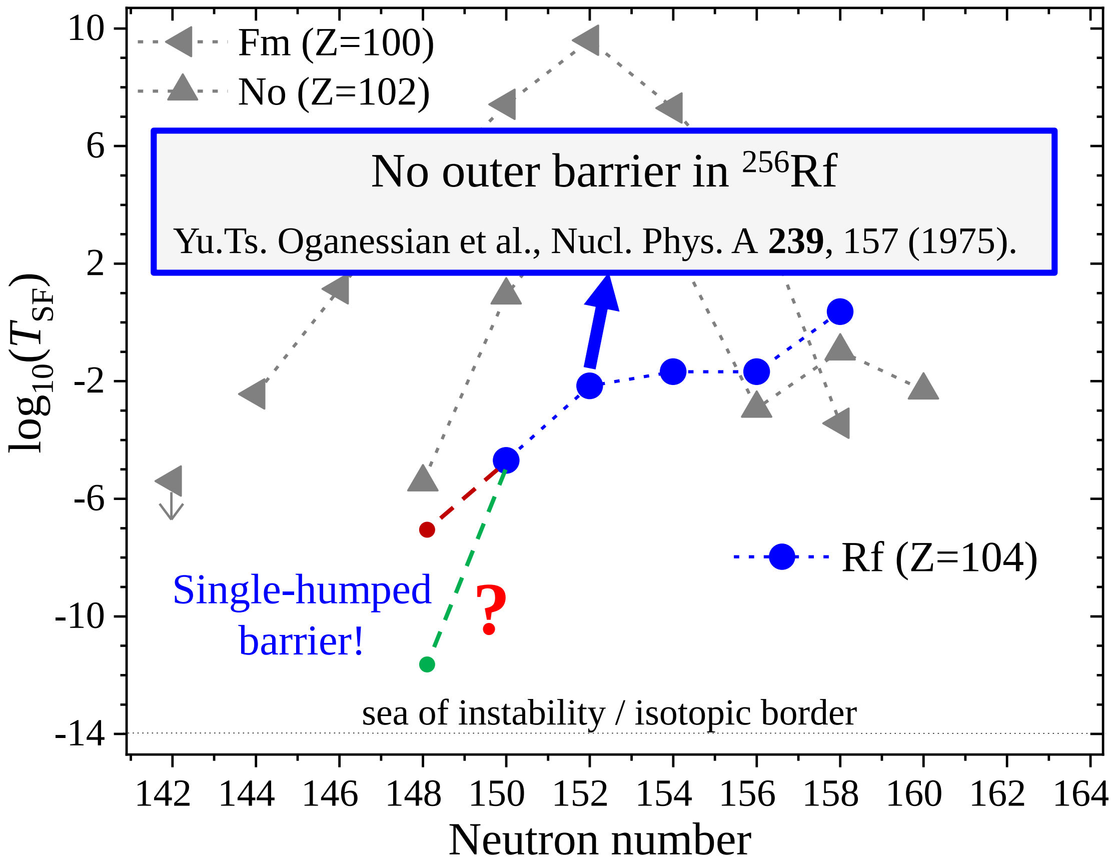
Fission-landscape of SHN: sea of instability

$T_{SF}(^{252}Rf) \approx 10^{-7}$ s

^{253}Rf: J. Khuyagbaatar et al., Phys. Rev. C. **104**, L031303 (2021).

$T_{SF}(^{252}Rf) \leq 10^{-12}$ s

^{253}Rf: A. Lopez-Martens et al., Phys. Rev. C. **105**, L021306 (2022).



Sea of instability ($<10^{-14}$ s)

- No atom and element exists
- Definition of isotope is not applicable

Fission-landscape of SHN: sea of instability

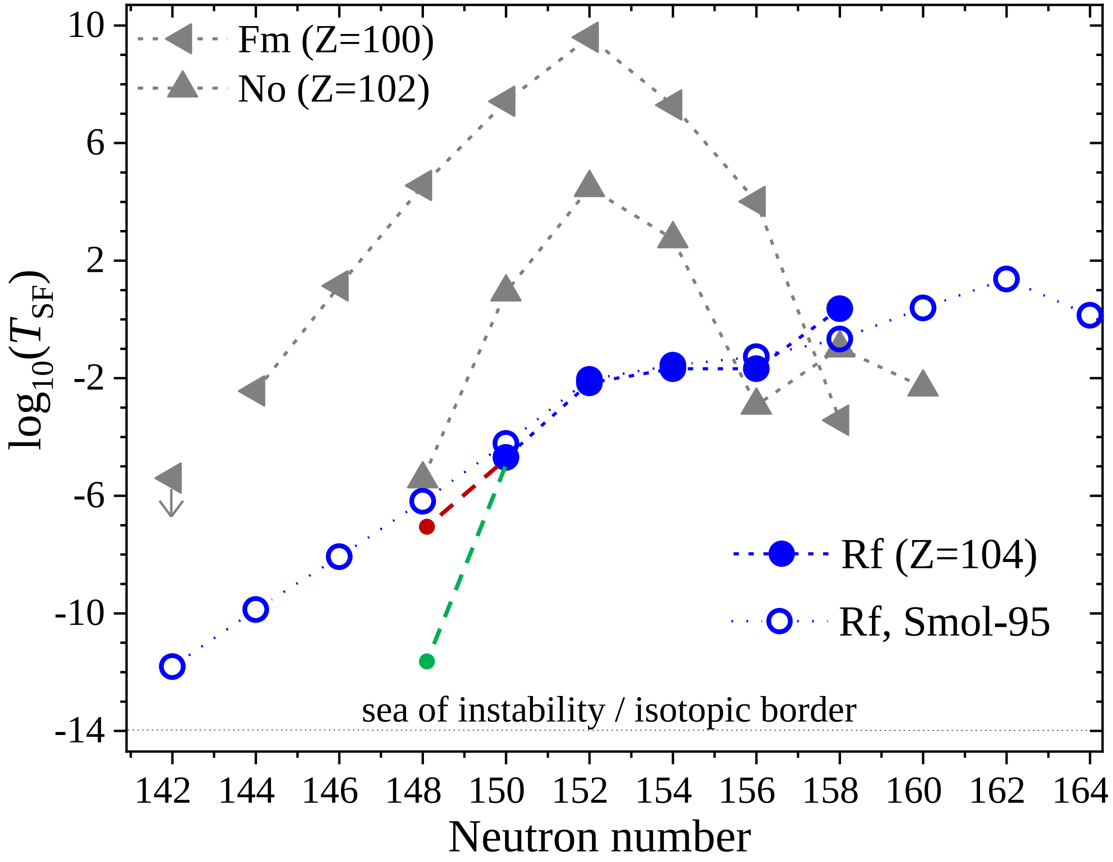
J. Khuyagbaatar @cold-fusion-50

$T_{SF}(^{252}Rf) \approx 10^{-7}$ s

^{253}Rf: J. Khuyagbaatar et al., Phys. Rev. C. **104**, L031303 (2021).

$T_{SF}(^{252}Rf) \leq 10^{-12}$ s

^{253}Rf: A. Lopez-Martens et al., Phys. Rev. C. **105**, L021306 (2022).



Sea of instability ($<10^{-14}$ s)

- No atom and element exists
- Definition of isotope is not applicable

Smol-95: R. Smolańczuk, J, Skalski and A. Sobiczewski, Phys. Rev.C **52** 1871 (1995)

Synthesis of ^{252}Rf: K-isomeric state

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$T_{SF}(^{252}Rf) \approx 10^{-7}$ s

^{253}Rf: J. Khuyagbaatar et al., Phys. Rev. C. **104**, L031303 (2021).

$T_{SF}(^{252}Rf) \leq 10^{-12}$ s

^{253}Rf: A. Lopez-Martens et al., Phys. Rev. C. **105**, L021306 (2022).

In-flight separators ~1 μs

K-isomeric states with half-lives longer than the ground states

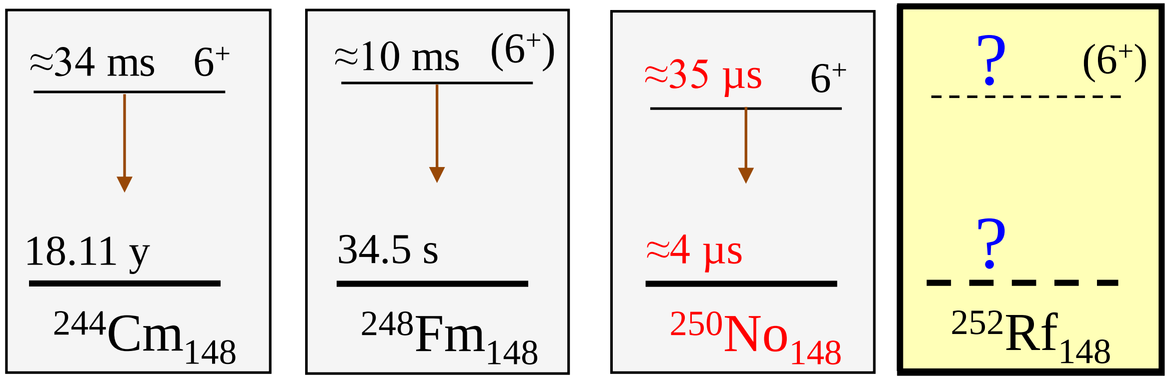
^{270}Ds (≈ 20 times longer)
S. Hofmann et al., Eur. Phys. J. A **10**, 5 (2001).

^{250}No (≈ 10 times longer)
A.V. Belozerov et al., Eur. Phys. J. A **16**, 447 (2003).
D. Peterson et al., Phys. Rev. C **74**, 014316 (2006).
A. Svirikhin et al., Phys. Part. Nucl. Lett. **14**, 571 (2017).
M. Tezekbayeva et al., Eura. J. Phys. Func. Mat. **3**, 300 (2019).
J. Kallunkathariyil et al., Phys. Rev. C **101**, 011301 (2020).

^{254}Rf (≈ 10 times longer)
H. M. David et al., Phys. Rev. Lett. **115**, 132502 (2015).

The $K^{\pi}=6^{+}$ isomeric states in N=148 isotones

F. Kondev, G. Dracoulis and T. Kibedi, ADNDT 103-104, 50 (2015).



K-isomeric state: Inverted fission-stability

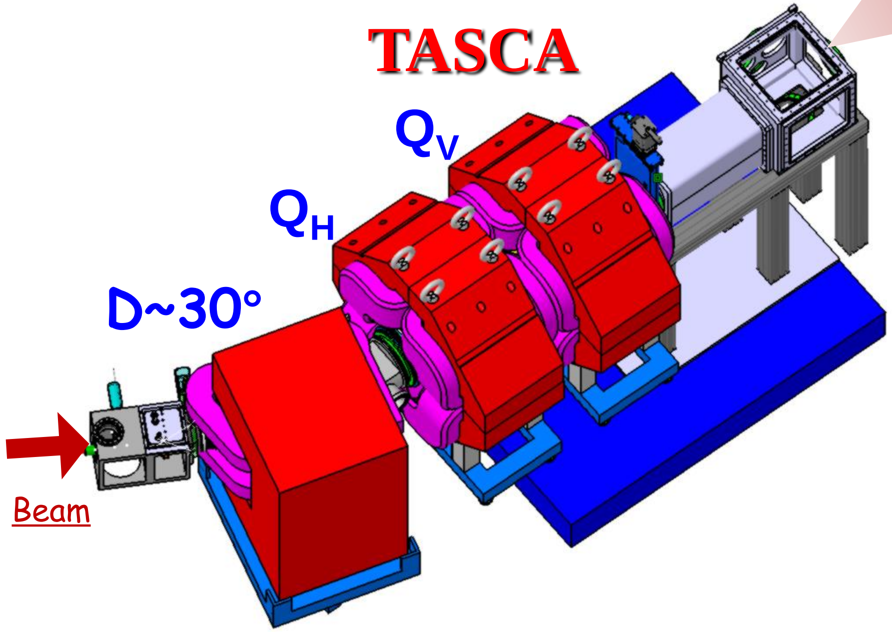
A. Baran and Z. Lojewski, Nucl. Phys. A **475**, 327 (1987).
F. R. Xu et al., Phys. Rev. Lett. **92**, 252501 (2004).
G. G. Adamian et al., Phys. Rev. C **81**, 024320 (2010).
H. L. Liu et al., Phys. Rev. C **89**, 044304 (2014).
J. Khuyagbaatar, Eur. Phys. J. A **58**, 243 (2022).

The gas-filled recoil separator TASCA

J. Khuyagbaatar @cold-fusion-50

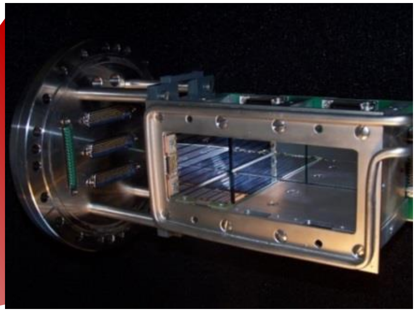
TransActinide Separator and Chemistry Apparatus

Beam: in pulse mode 5 ms-long and 50Hz
Penning and ECR ions sources + UNILAC
^{1}H - ^{238}U with energies 11 MeV/u



Separation by $B\rho = mv/\langle q \rangle$

J. Khuyagbaatar *et al.*, NIM A **689**, 40 (2012)
J. Khuyagbaatar *et al.*, PRA **88**, 042703 (2013)



Focal plane detector

Physics

Detection system

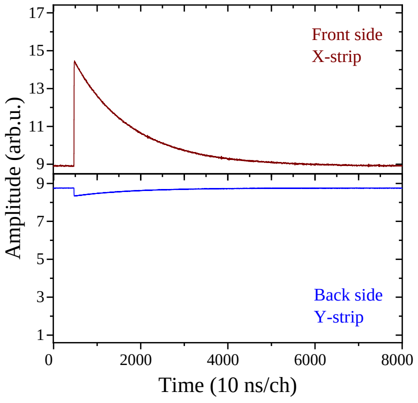
MWPC
Stop: 2 DSSD 72*48 mm^2
Box: 8 DSSD and Veto: 2 SSD
Gamma: BEGe detectors

DAQ system

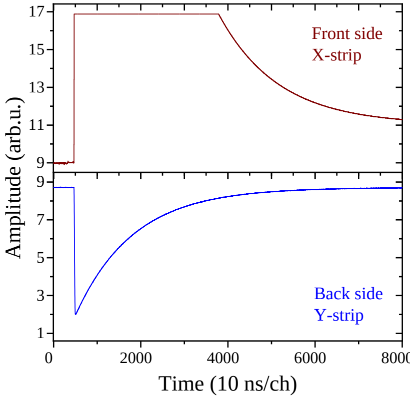
Febex
Mbs
go4

Experiment Electronics Department, GSI

Signal of α particle



Signal of fission fragments



J. Khuyagbaatar et al.,

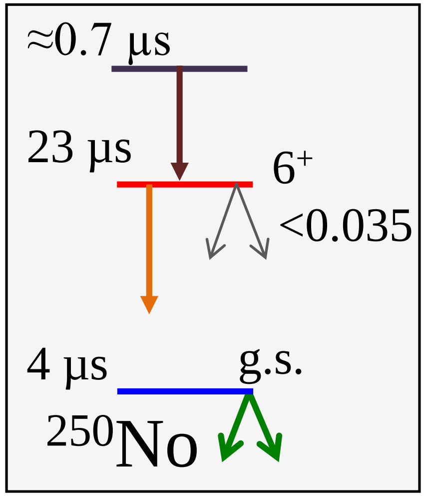
Element Ts (Z=117)
Phys. Rev. C **99**, 054306 (2019).
Phys. Rev. Lett. **112**, 172501 (2014).
Search for elements 119 and 120
Phys. Rev. C **102**, 064602 (2020).

J. Khuyagbaatar et al.,

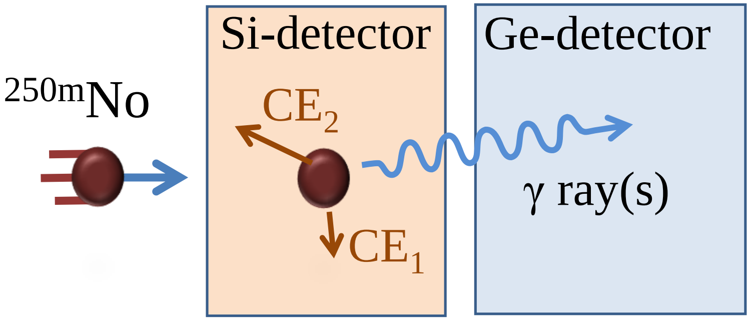
N=126 shell and discovery of ^{221}U
Phys. Rev. Lett. **115**, 242502 (2015).
EC-delayed fission
Phys. Rev. Lett. **125** 142504 (2020)
Phys. Rev. C **109**, 034311 (2024).

J. Khuyagbaatar @cold-fusion-50

^{254}Rf
J. Khuyagbaatar *et al.*, Nucl. Phys . A **994**, 121662 (2020)
^{256}Rf
J. Khuyagbaatar *et al.*, Phys. Rev. C **103**, 064303 (2021)
^{250}No
J. Khuyagbaatar *et al.*, Phys. Rev. C **106**, 024309 (2022)



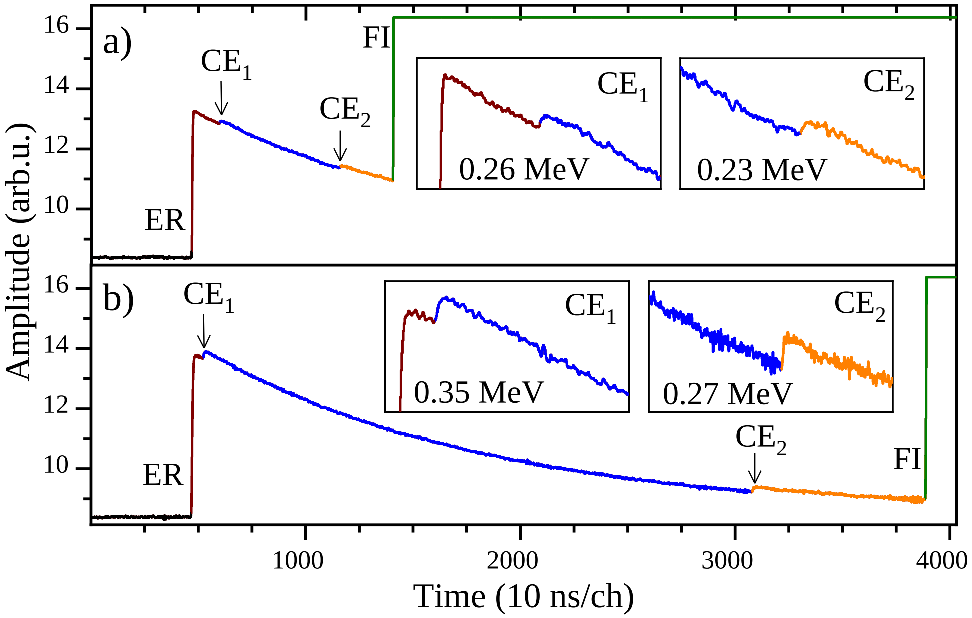
Two quasi-particle K-isomeric states are populated during the de-excitation of CN with probabilities >10%.

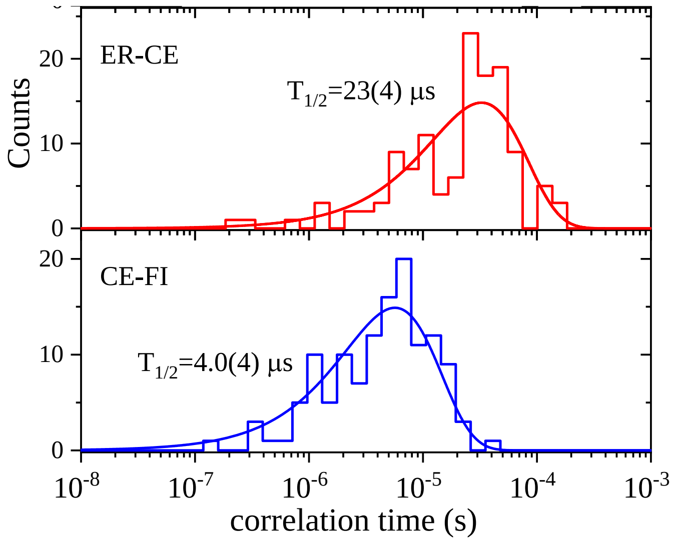


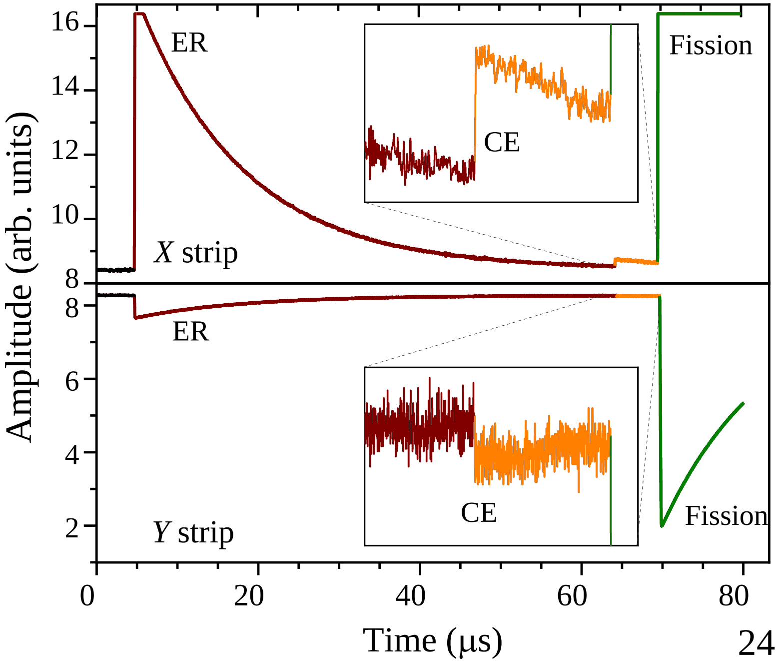
Low-energy and low-ionizing signal
$E(CE)=E_{CE1} + E_{CE2} + \ldots$

No direct fission from K-isomeric state was identified ($T_F > 160 \cdot T_{SF}$)

Discovery of second K-isomer





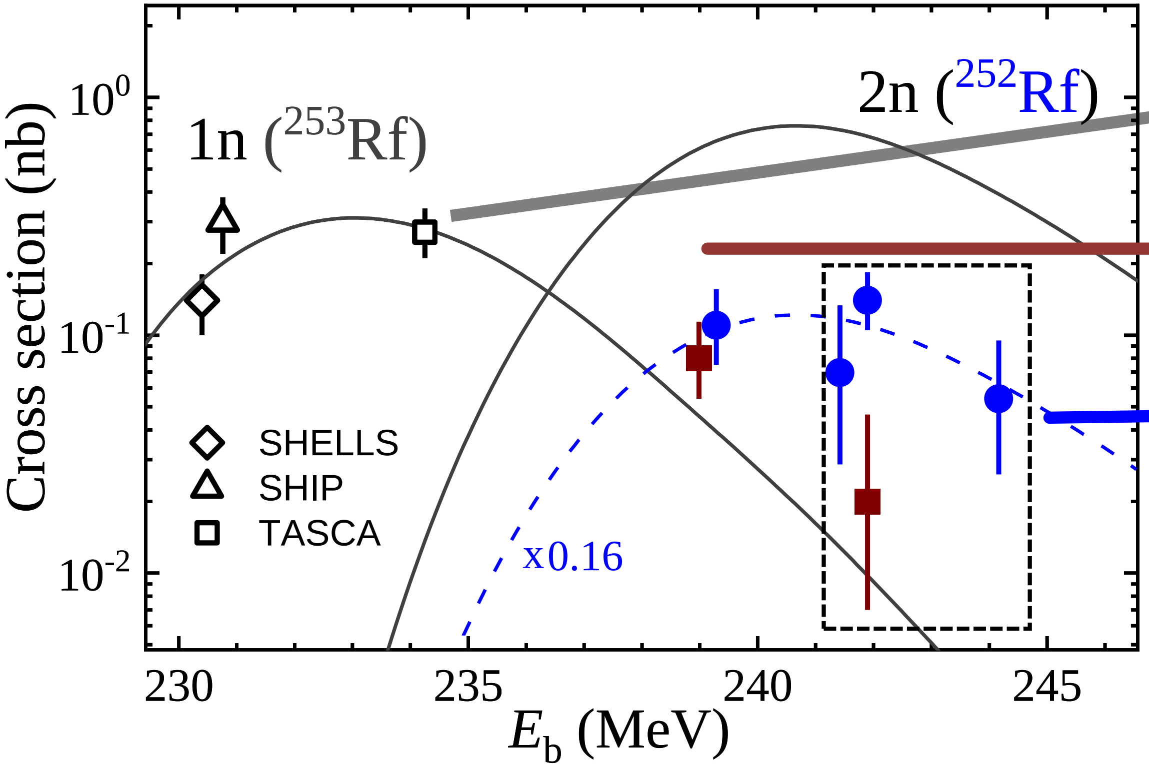


Search for ^{252}Rf @TASCA

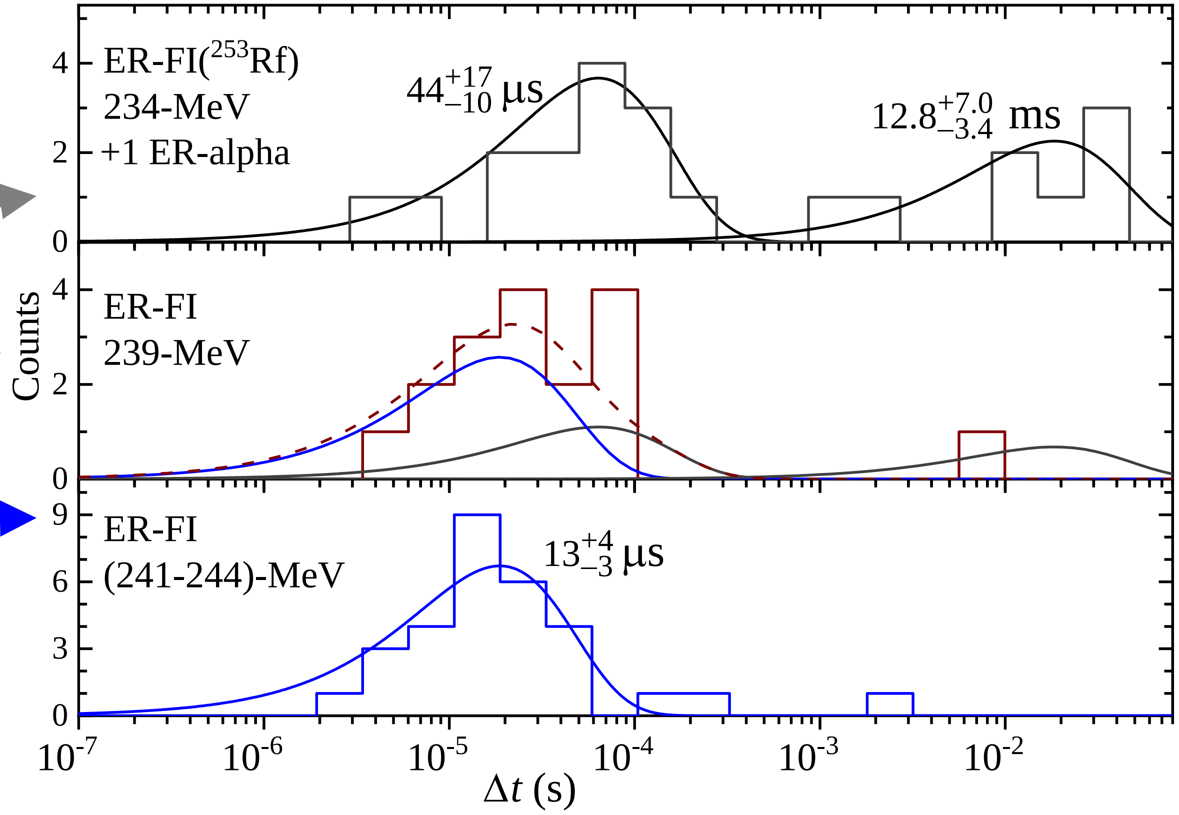
J. Khuyagbaatar @cold-fusion-50

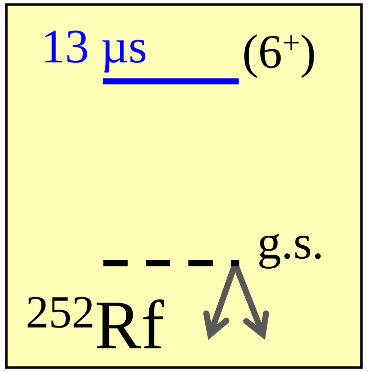
J. Khuyagbaatar, P. Mosat *et al.*, under review with Phys. Rev. Lett.

^{50}Ti+^{204}Pb: HIVAP calculation



ER-Fission correlation





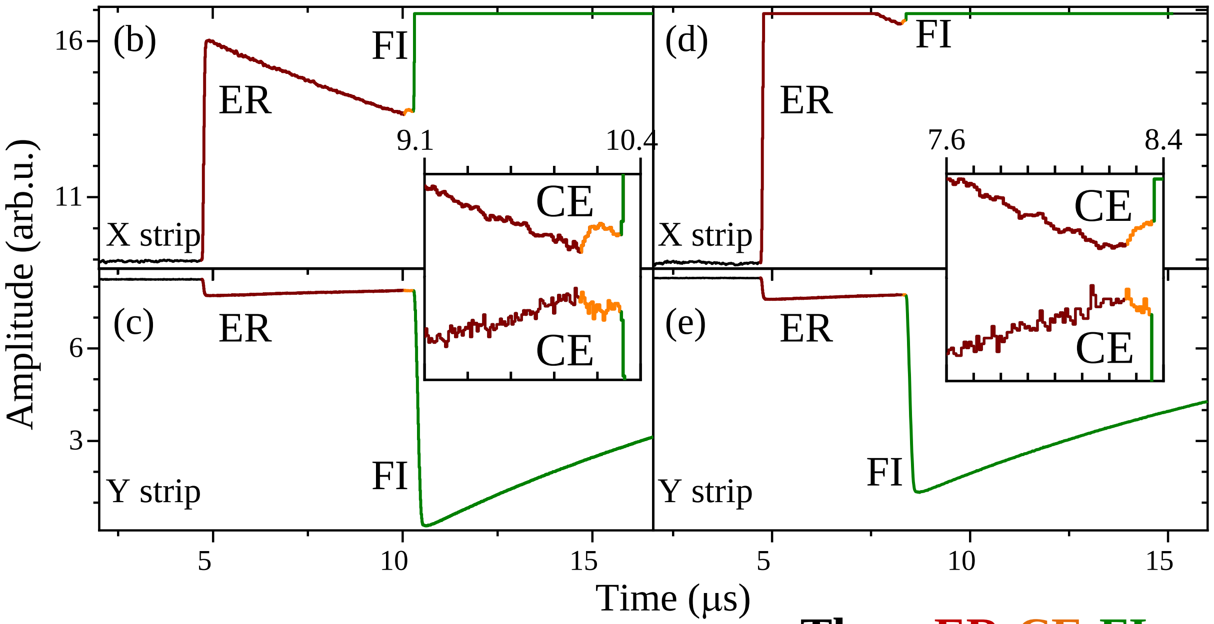
Theoretical fission half-life for 6$^+$: **50 μs**
J. Khuyagbaatar, Eur. Phys. J. A **58**, 243 (2022).

Population probability of 2qp states: ≥ **10%**

SHIP: F.P. Hessberger et al., Z. Phys. A **359**, 415 (1997).
TASCA: J. Khuyagbaatar et al., Phys. Rev. C. **104**, L031303 (2021).
SHELS: A. Lopez-Martens et al., Phys. Rev. C. **105**, L021306 (2022).

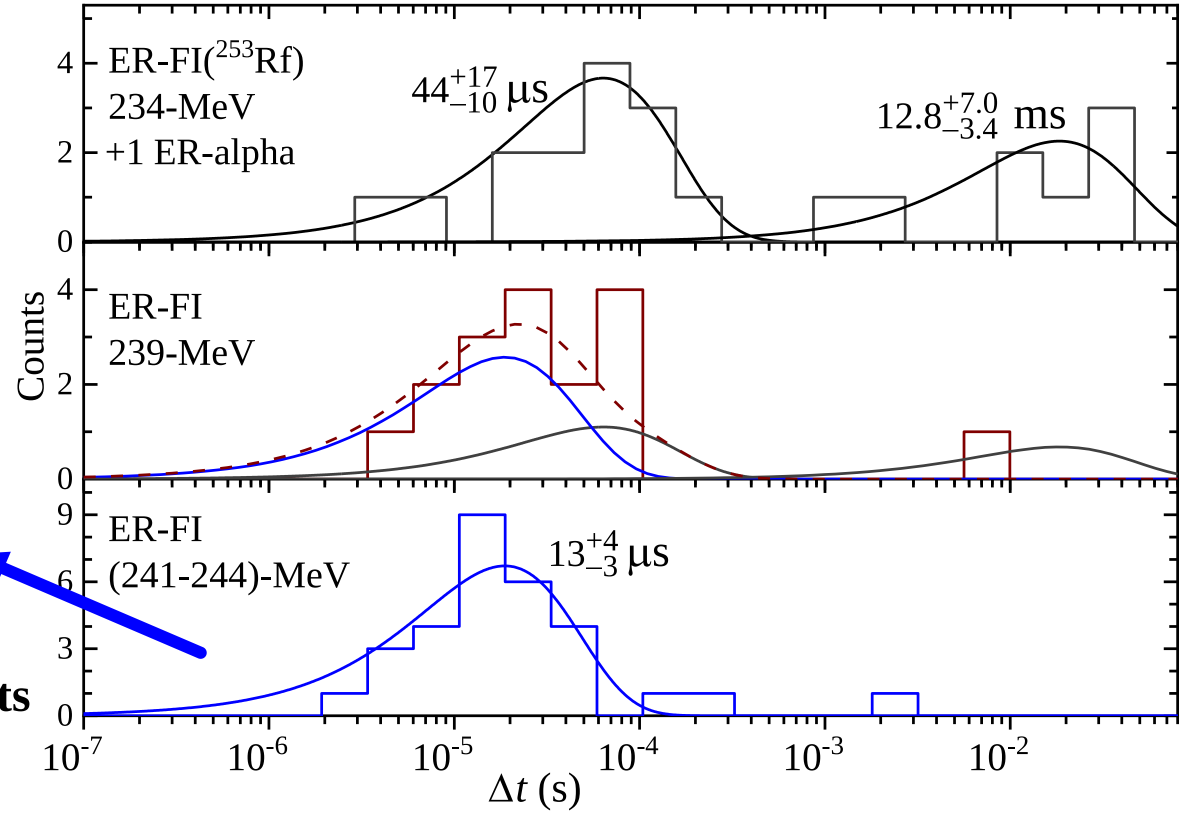
Search for ^{252}Rf @TASCA

J. Khuyagbaatar, P. Mosat *et al.*, under review with Phys. Rev. Lett.



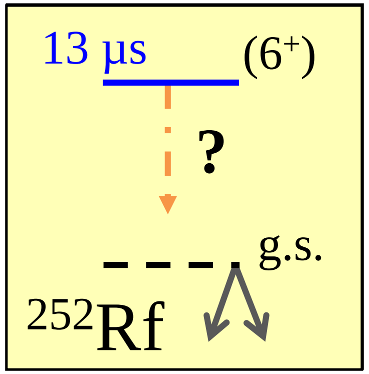
Three ER-CE-FI events

ER-Fission correlation



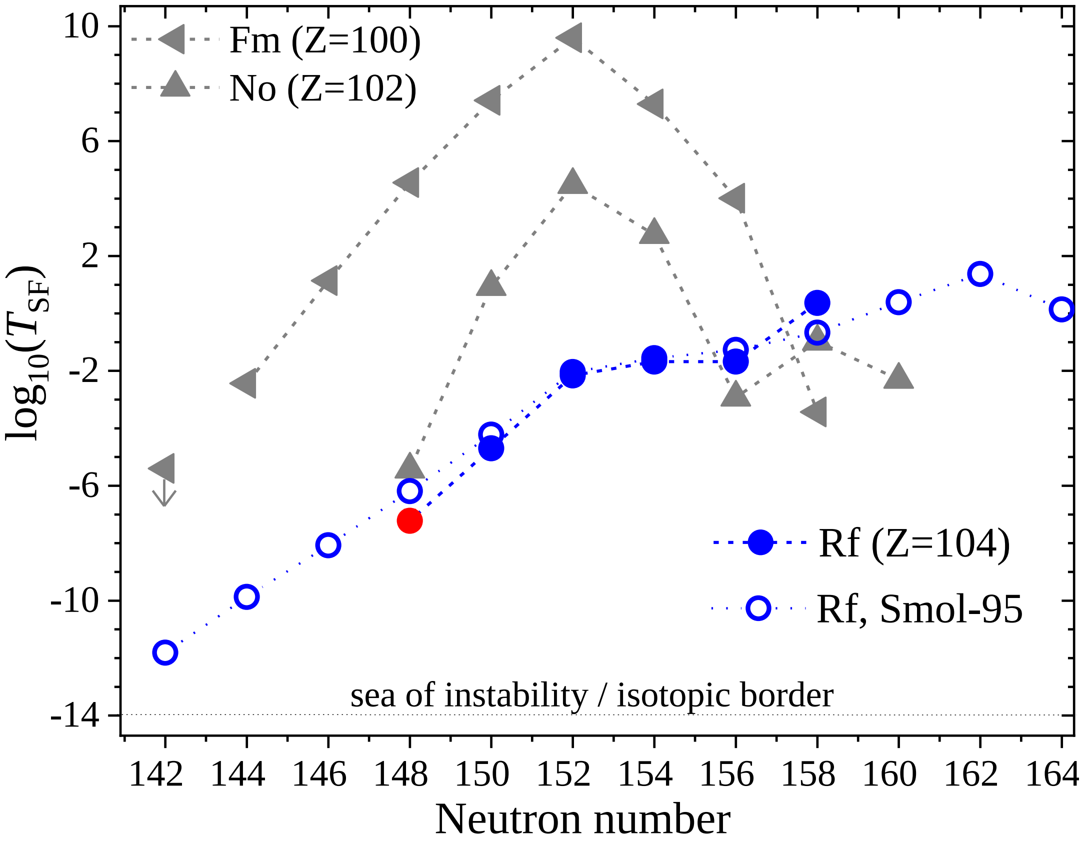
The K-isomeric state with inverted fission stability (>200 times longer)

The shortest-lived known spontaneous fissioning nucleus

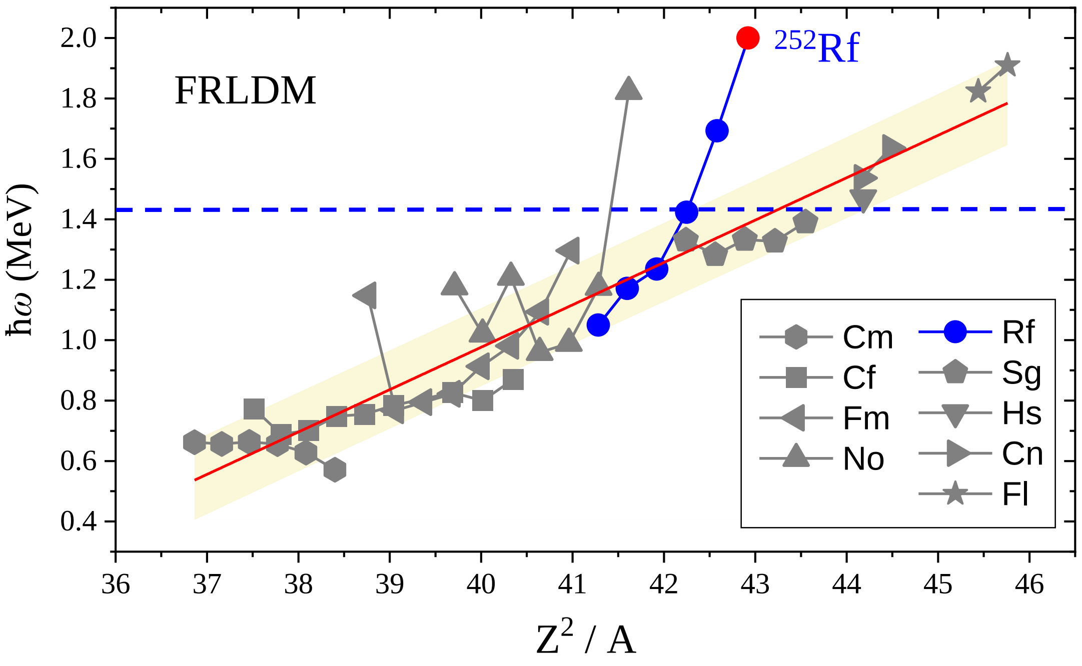


Systematics of spontaneous fission half-lives: Rf isotopes

J. Khuyagbaatar @cold-fusion-50



J. Khuyagbaatar, Nucl. Phys. A **1002**, 121958 (2020).

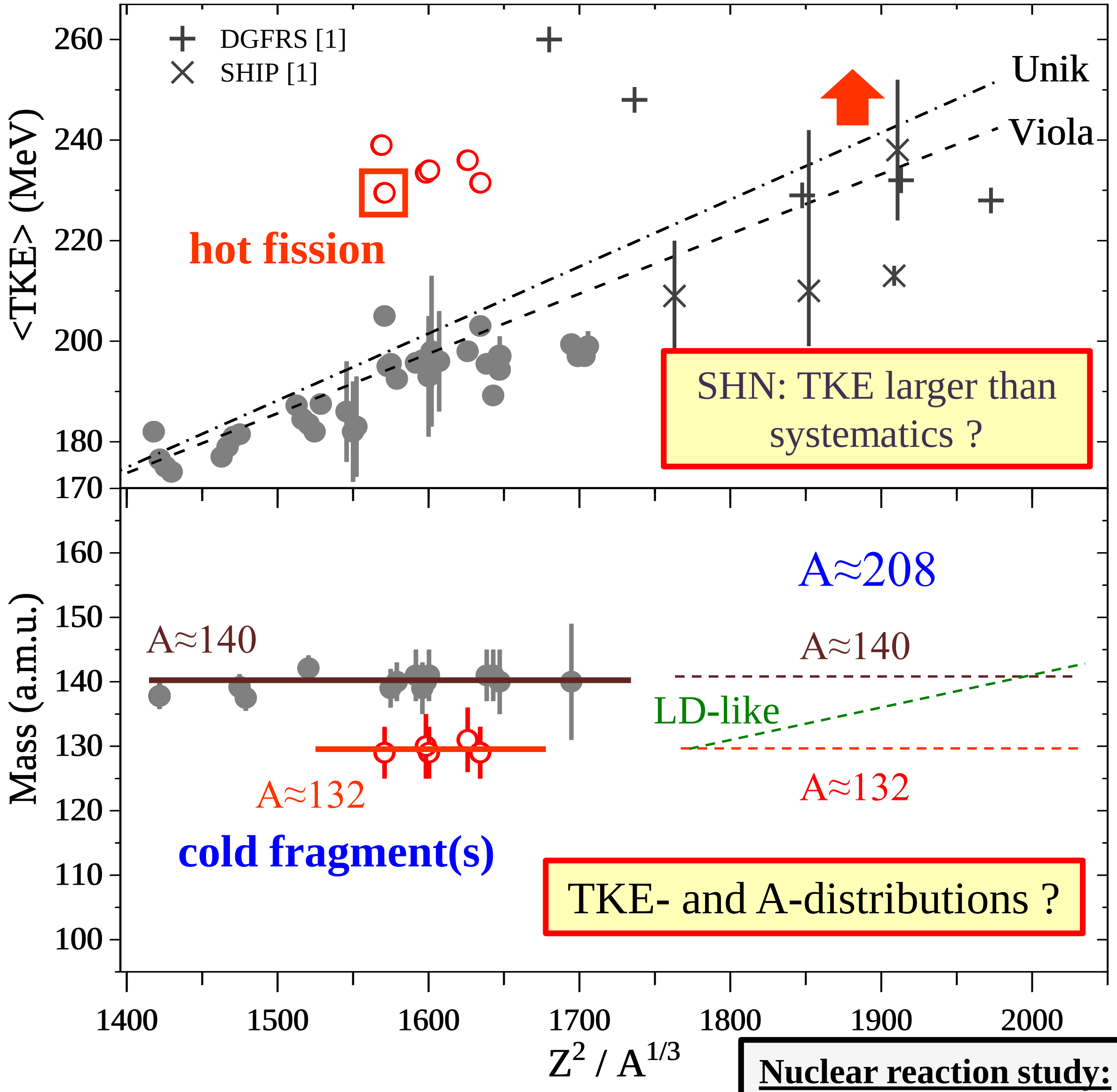


$T_{SF}(^{252}Rf)$ pushes the limit of known fission half-lives of SHN down by about 10^2.

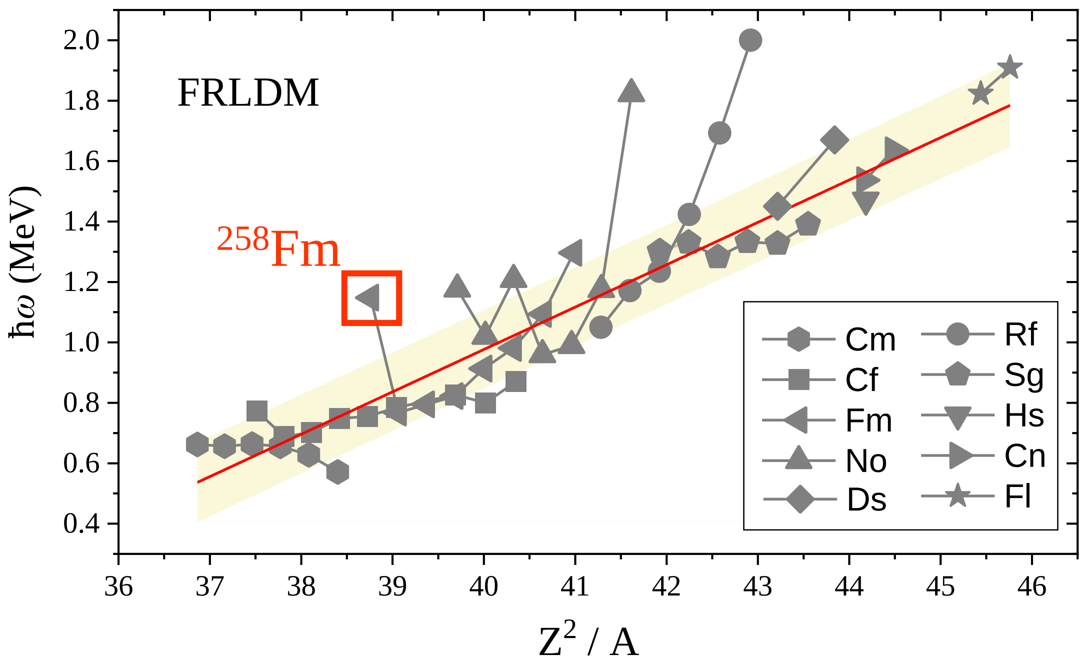
Isotopic border of Rf is not yet reached.

Barrier widths vs energy and mass distribution of fission fragments

J. Khuyagbaatar @cold-fusion-50



What does mean the narrow-barrier width of SHN ?



Nuclear reaction study: (A=132)

SH compound nuclei @E* > 20 MeV
M.G. Itkis et al., NPA **944**, 204 (2015)

TKE- and A-distributions (Theory)

N. Carjan et al.,, NPA **968**, 453 (2017)
S. A. Giuliani et al., RMP. **91**, 011001 (2019)
Z. Matheson et al., PRC **99**, 041304(R) (2019).
C. Ishizuka et al., PRC **101**, 011601(R) (2020)
M. Albertsson et al., EPJ. A **56**, 46 (2020)
P. V. Kostryukov et al., CPC **45** 124108 (2021)
…

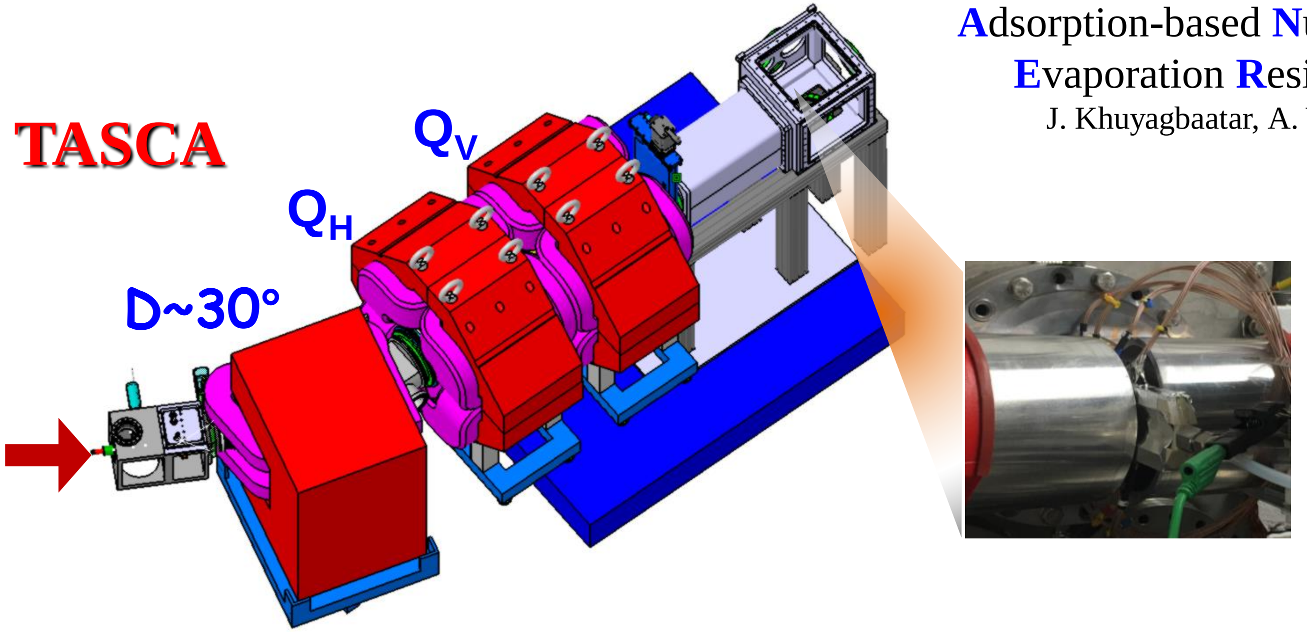
[1] F.P. Hessberger, Eur. Phys. J. A **53**, 75 (2017).

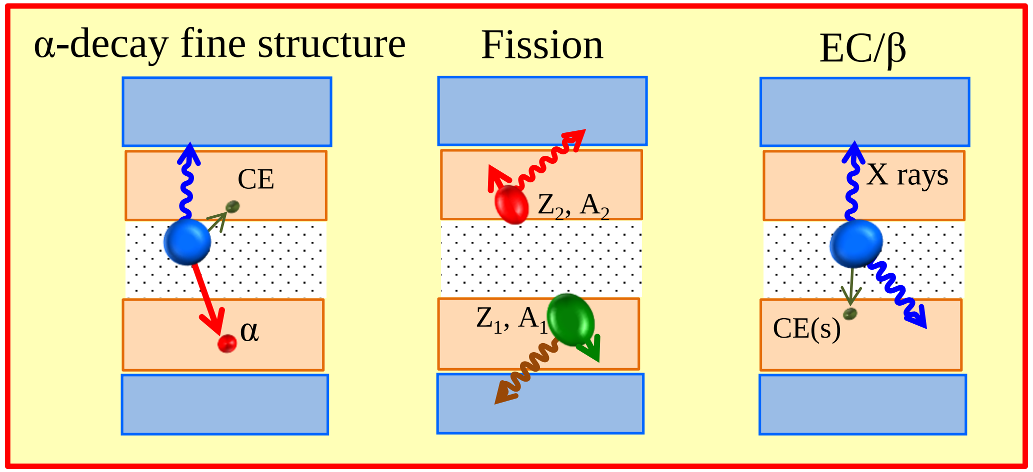
ANSWERS to questions on the fission and structure of SHN

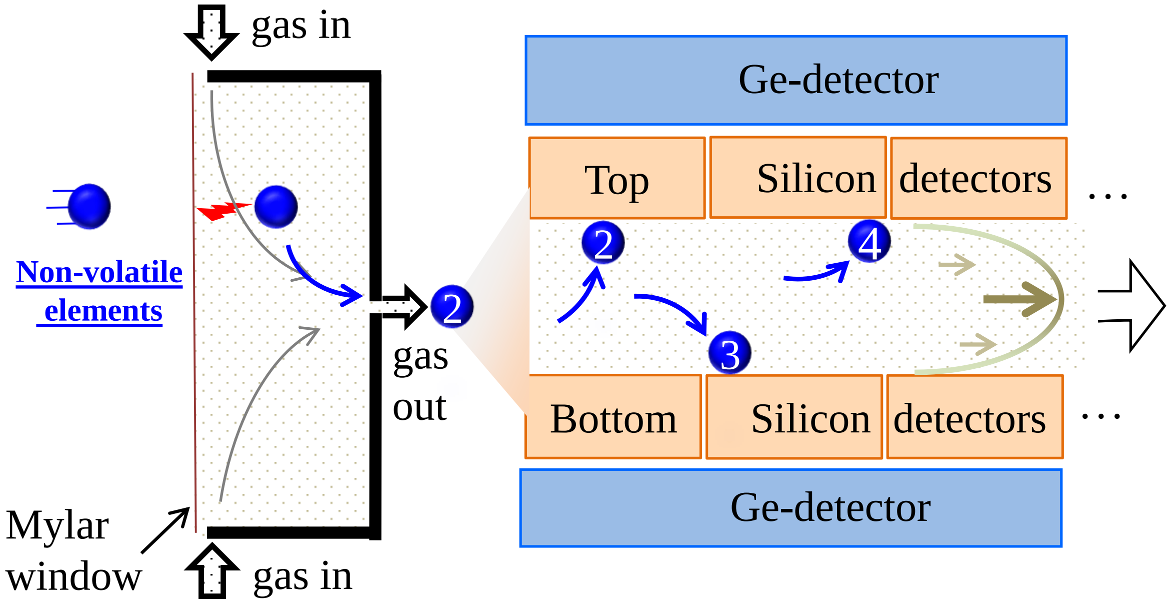
J. Khuyagbaatar @cold-fusion-50

Adsorption-based **N**uclear **S**pectroscopy **W**ithout **E**vaporation **R**esidue **S**ignal (**ANSWERS**)

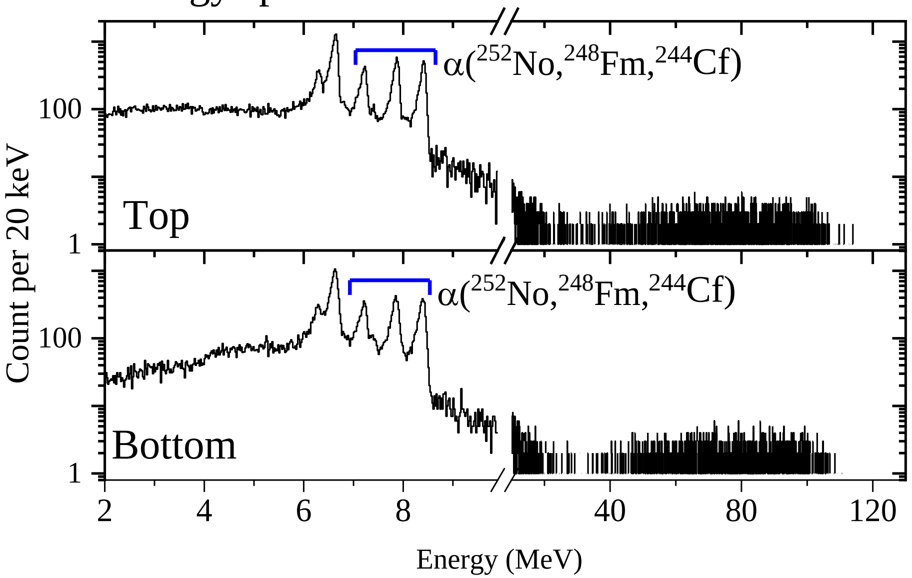
J. Khuyagbaatar, A. Yakushev et al,. to be published







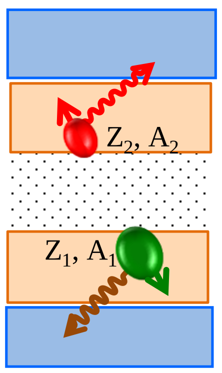
Energy spectra from the $^{48}Ca + ^{206}Pb$ reaction

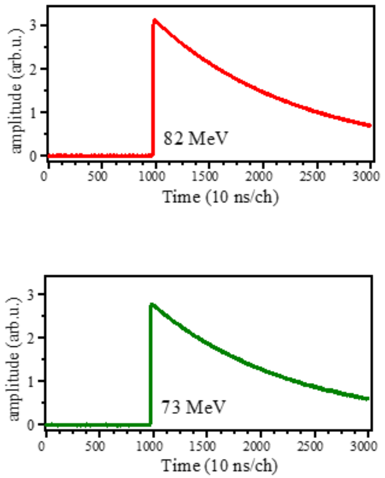


ANSWERS: Fission property of ^{252}No (preliminary)

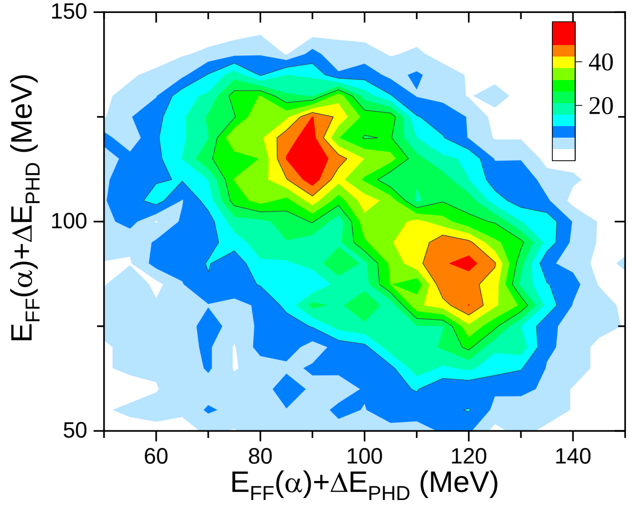
J. Khuyagbaatar @cold-fusion-50

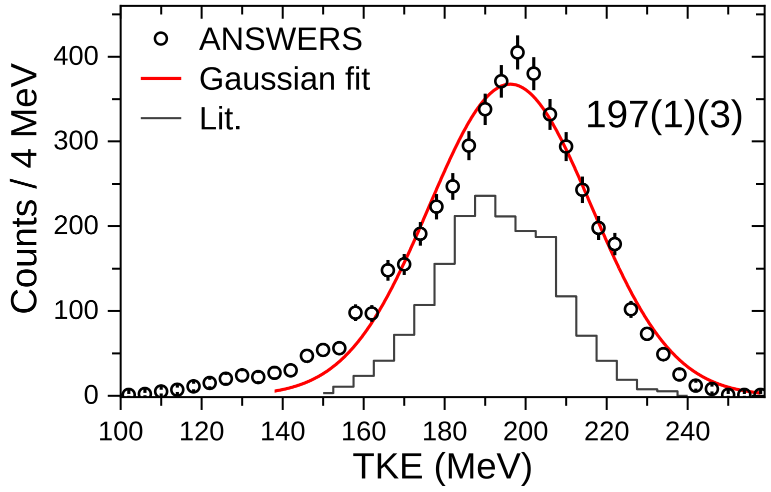
Fission

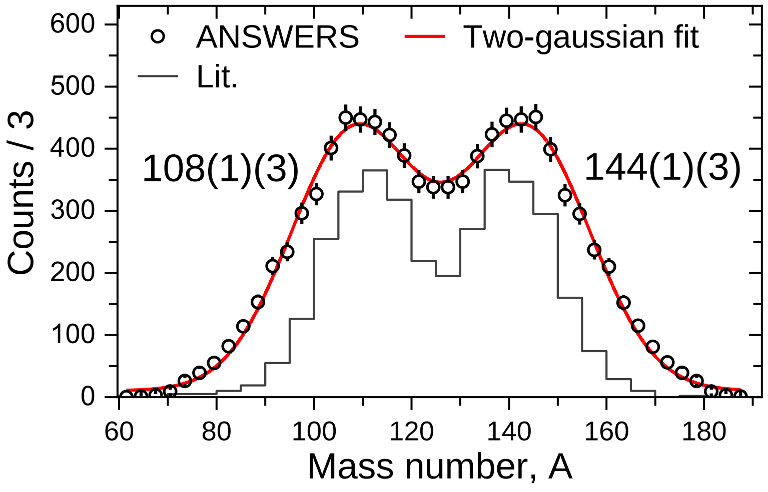




Cold-fusion: ^{48}Ca+^{208}Pb
>**5000** coincidence fission events







Hot-fusion: ^{12}C+^{244}Cm (Lit.)
J.F. Wild et al., J. All. Com. **213/214**, 86 (1994).
1741 coincidence fission events

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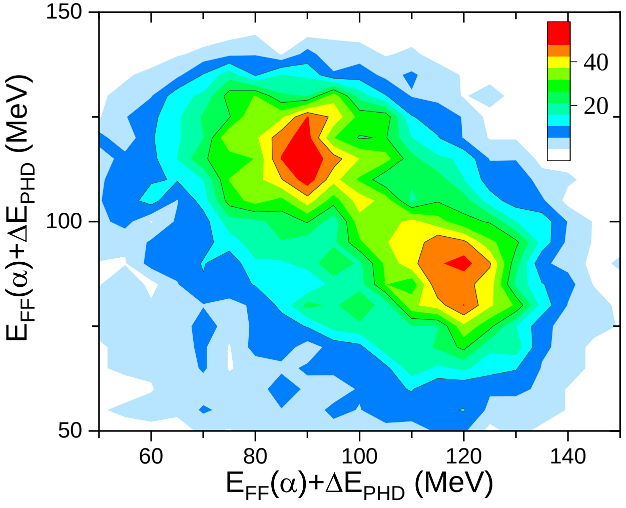
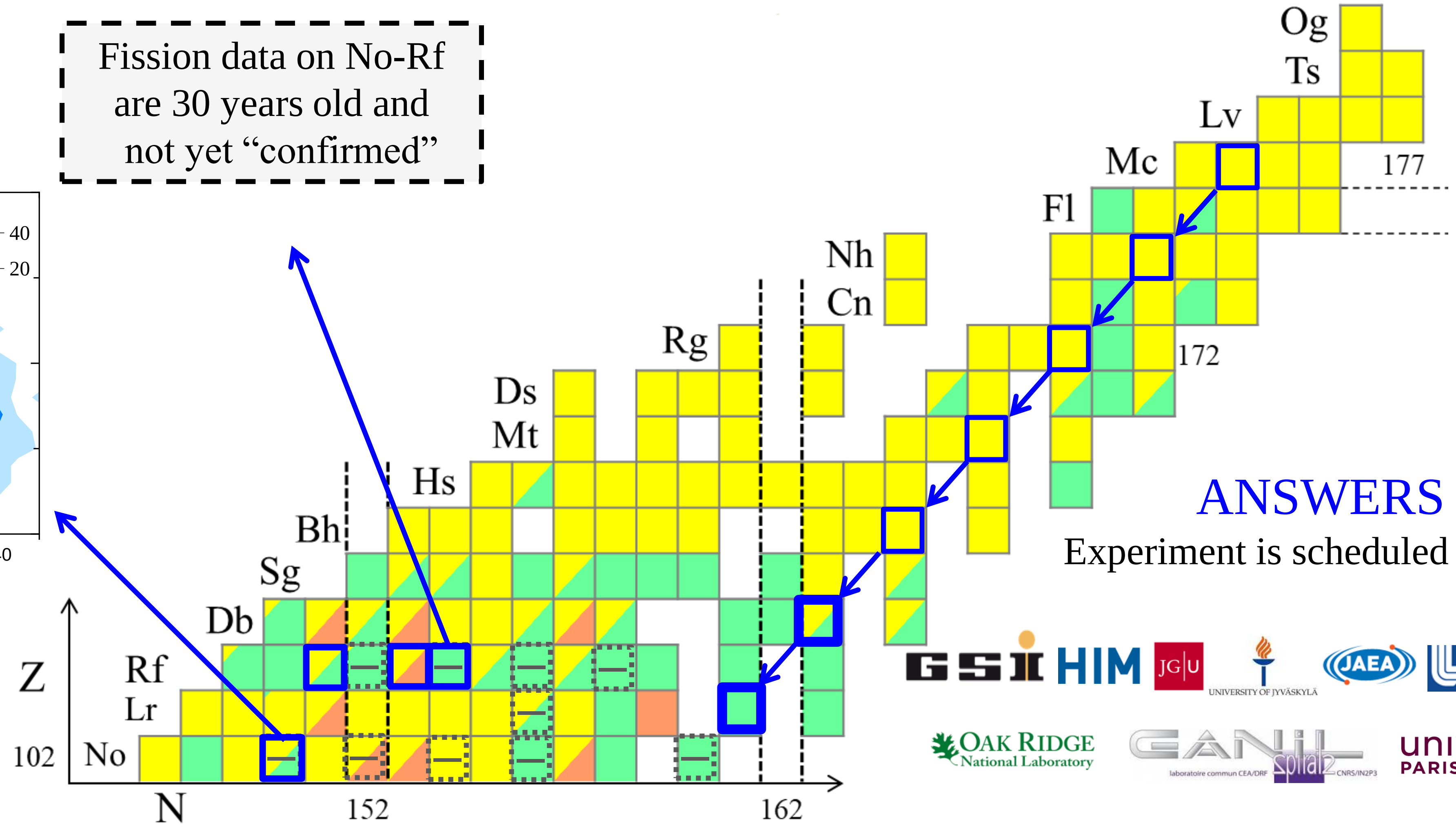
ANSWERS



Fission data on No-Rf are 30 years old and not yet “confirmed”



ANSWERS

Experiment is scheduled in 2025

Summary and conclusion

Cold-fusion
- Great impact on the nuclear physics
- Still the main source for study of SHN
- Still has a potential to explore yet unknown features

Fission

- The stability of SHN and complex process
- Fission barriers of SHN suggestively have narrow widths
- Isotopic border of Rf is yet to be reached
- The TKE and A-distributions are hot topics

Intensive fusion and fission studies @**TASCA** are ongoing.
Discovery of sub-µs SF ^{252}Rf and K-isomer
Benchmark for the spontaneous fission
Benchmark for the inverted fission-stability

ANSWERS is already exploring the fission, beta decay and α-decay fine structure of superheavy nuclei

Thank you for your attention.

The part of results presented here are based on the experiments U308, U328 and G-22-00034, which were performed at the beam line X8/TASCA at GSI in the frame of FAIR Phase-0.