

# On the properties of superheavy nuclei

J. Khuyagbaatar

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany



FISSION 2026, Chamrousse, France

9-13 March 2026

## Introduction:

- Heaviest nuclei and fission landscape of superheavy nuclei

## Semi-empirical approaches: The fission-barrier shape

- The ground-state fission
- The excited-state fission

## Semi-empirical approaches: The fission hindrance

- The K-isomeric states (clouds of stability)

## Clouds of stability (K-isomeric state) vs sea of instability (ground state)

## Search for K-isomeric states new isotopes @TASCA

- $^{250}\text{No}$ ,  $^{252}\text{Rf}$ ,  $^{257}\text{Sg}$ , and  $^{259}\text{Sg}$



## Summary and conclusion

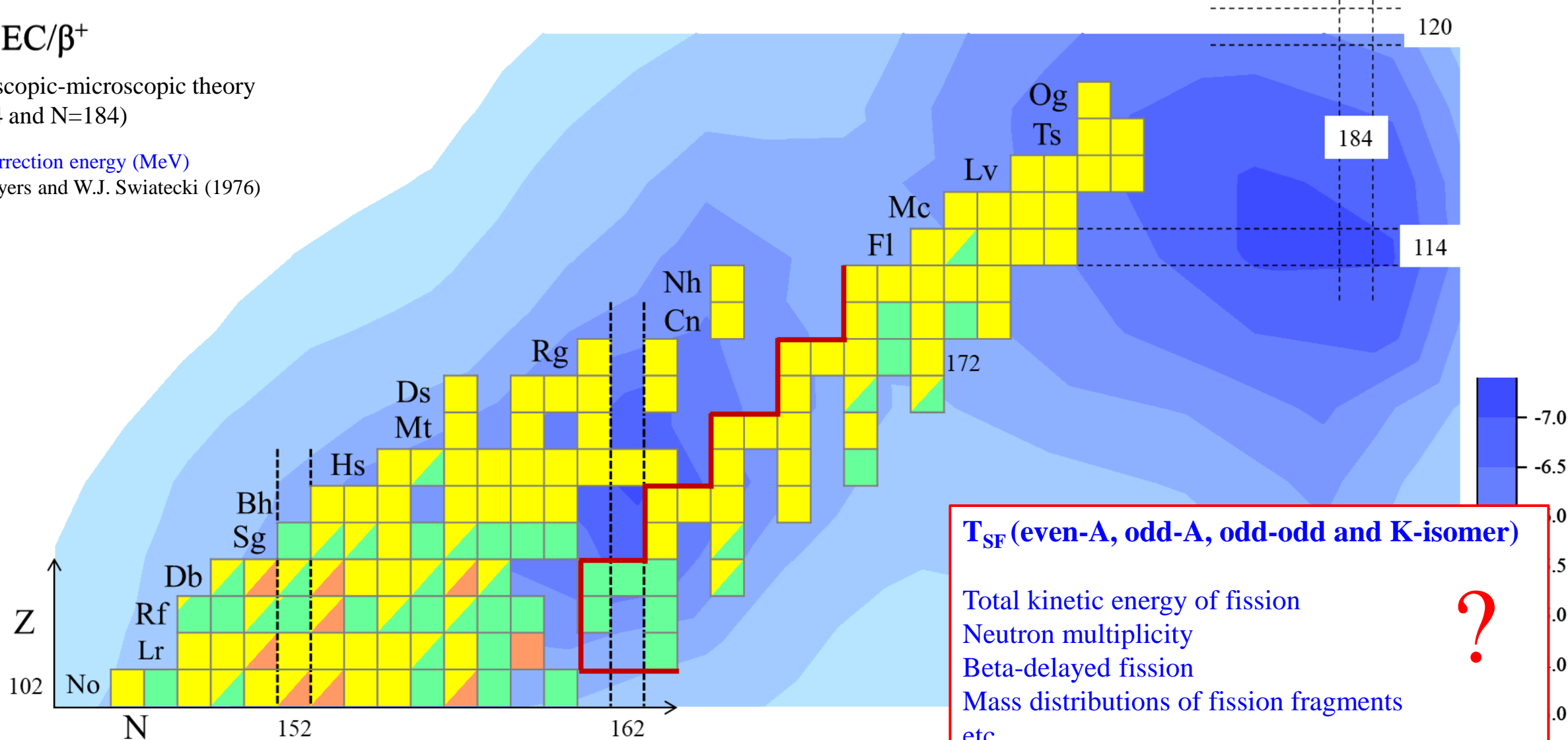
■  $\alpha$  ■ Fission

■ EC/ $\beta^+$

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

Shell correction energy (MeV)

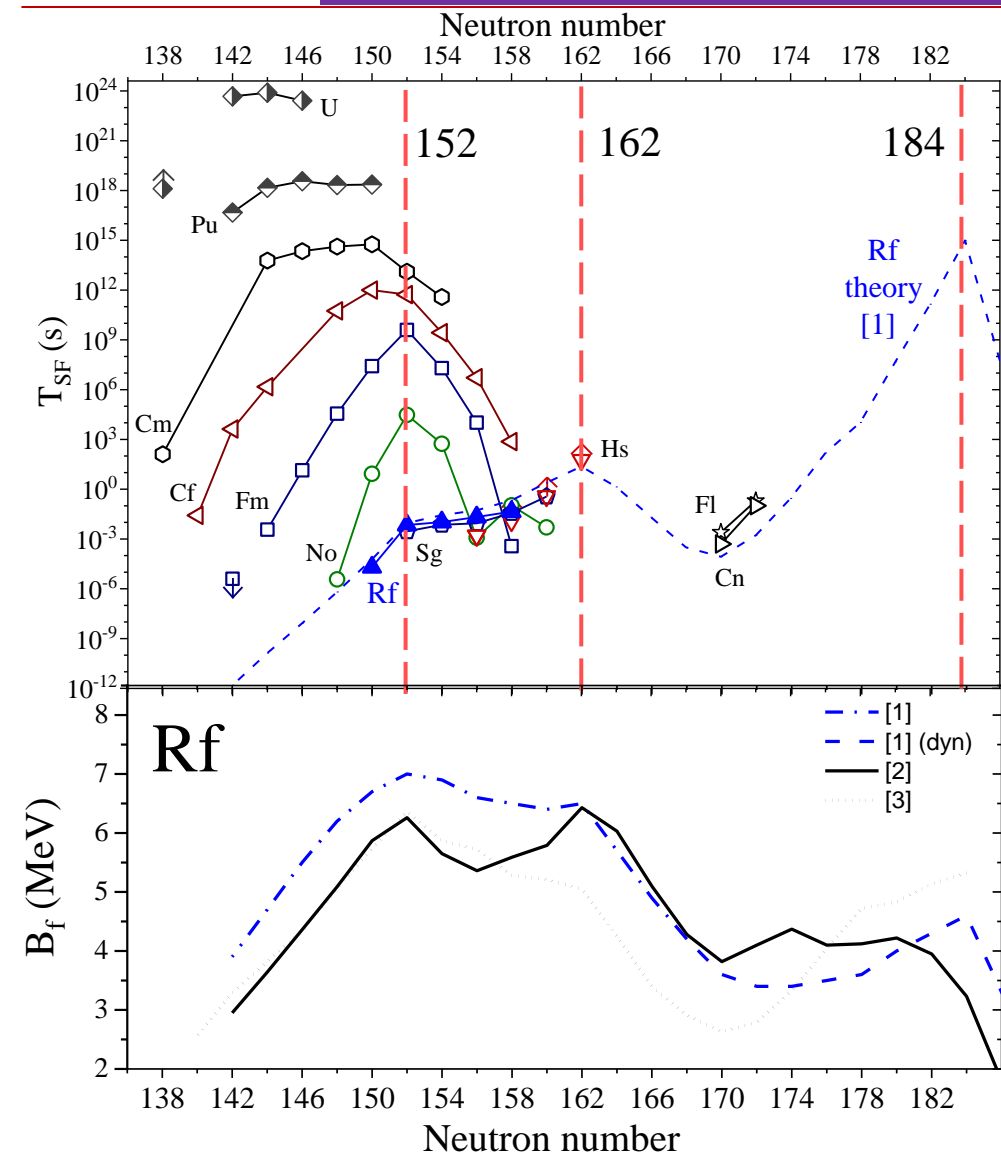
W.D. Myers and W.J. Swiatecki (1976)



**$T_{SF}$  (even-A, odd-A, odd-odd and K-isomer)**

Total kinetic energy of fission  
Neutron multiplicity  
Beta-delayed fission  
Mass distributions of fission fragments  
etc.,

?

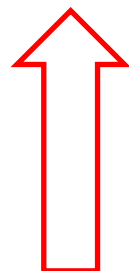


**Experiment**  
 $T_{SF}$  of even-even isotopes  
define the fission-landscape

$T_{SF}$  (exp)

≠

$T_{SF}$  (theory)



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

Macroscopic-microscopic  
Self-consistent microscopic approaches

[1] R. Smolańczuk, J. Skalski and A. Sobiczewski, Phys. Rev.C **52** 1871 (1995)

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

[3] M. Kowal, P. Jachimowicz, and A. Sobiczewski, Phys. Rev. C **82** 014303 (2010)

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

J. Khuyagbaatar @FISSION 2026

## Semi-empirical approaches

Formula for  $T_{SF} \sim Z^2/A, \Delta M, Z, N$   
W. J. Swiatecki-1955

V. E. Viola Jr. and G. T. Seaborg -1966

C. Xu and Z. Ren- 2005

K.P. Santhosh etc.,-2010

....

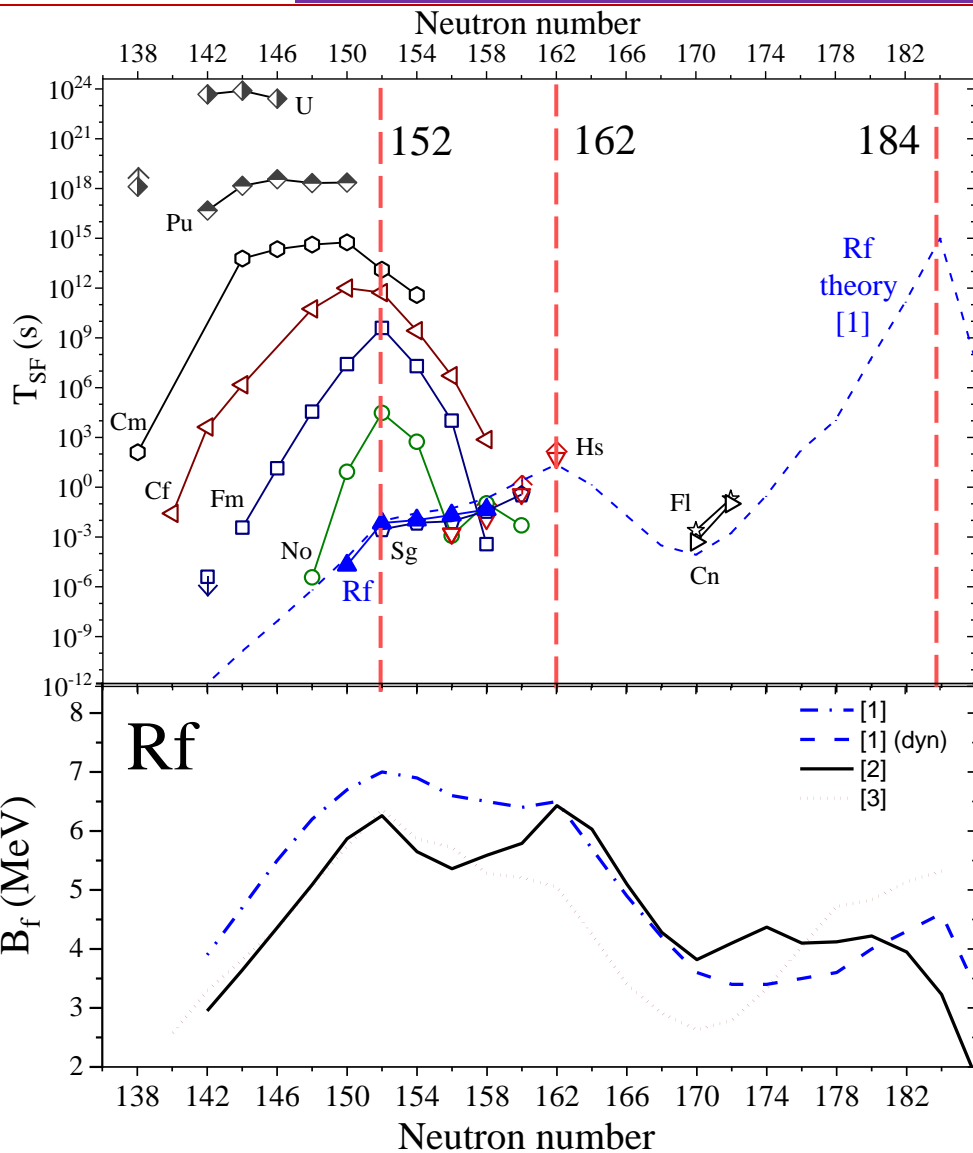
The classical formula for  $T_{SF} \sim$  barrier height and shape

D. L. Hill and J. A. Wheeler -1953

V.E. Viola and B.D. Wilkins – 1966

F. P. Heßberger et al., - 1986

... **Fission-barrier shape**



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

$T_{SF}(\text{exp})$   
//  
 $T_{SF}(\text{theory})$

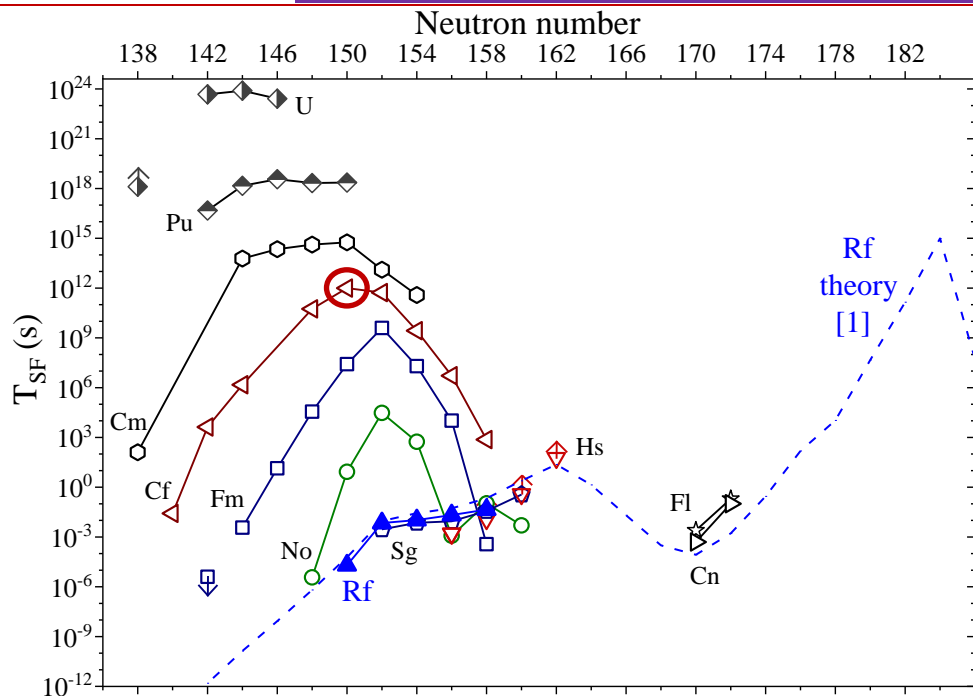
**Theory**  
 $B_f$  (Height): Global variable  
Shape: Local variable

Macroscopic-microscopic  
Self-consistent microscopic approaches

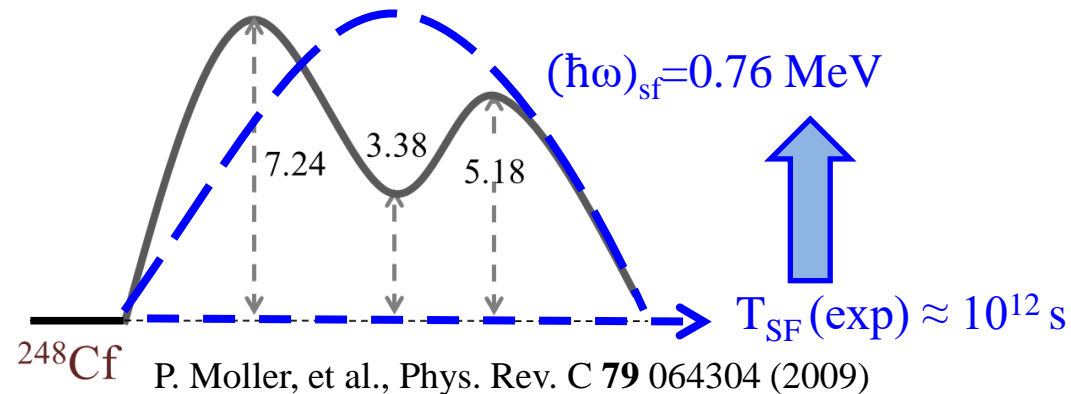
[1] R. Smolańczuk, J. Skalski and A. Sobiczewski, Phys. Rev.C **52** 1871 (1995)  
[2] P. Moller, et al., Phys. Rev. C **79** 064304 (2009)  
[3] M. Kowal, P. Jachimowicz, and A. Sobiczewski, Phys. Rev. C **82** 014303 (2010)

# Semi-empirical approaches

## The fission-barrier shape



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

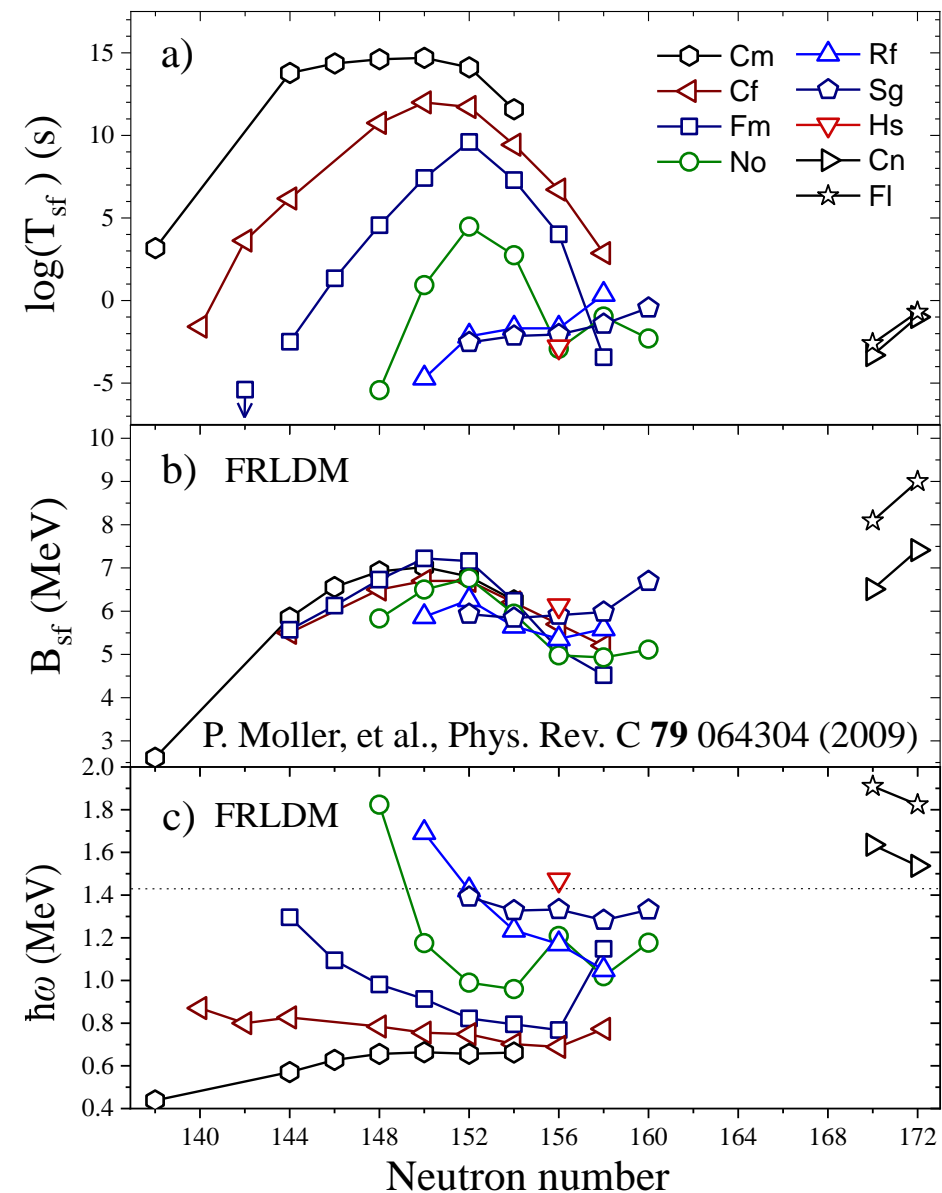


### Fission probability (parabolic-shaped barrier)

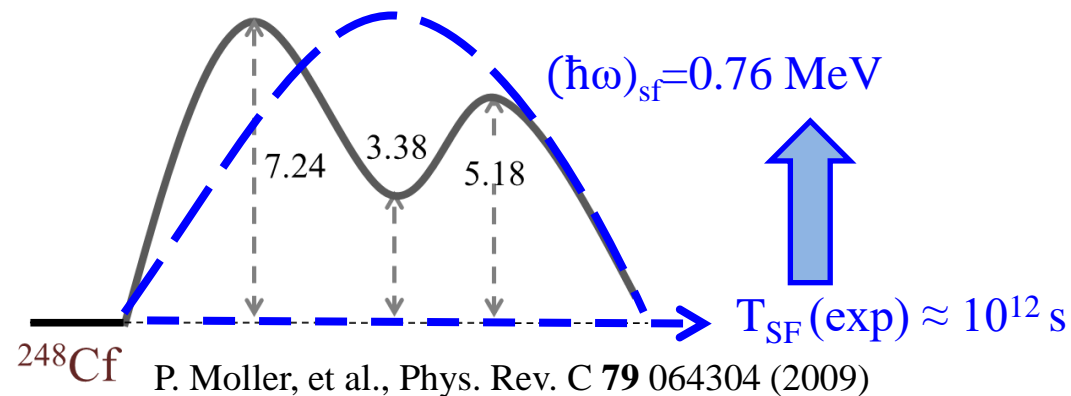
D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).

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

[1] R. Smolańczuk, J. Skalski and A. Sobiczewski, Phys. Rev.C **52** 1871 (1995)



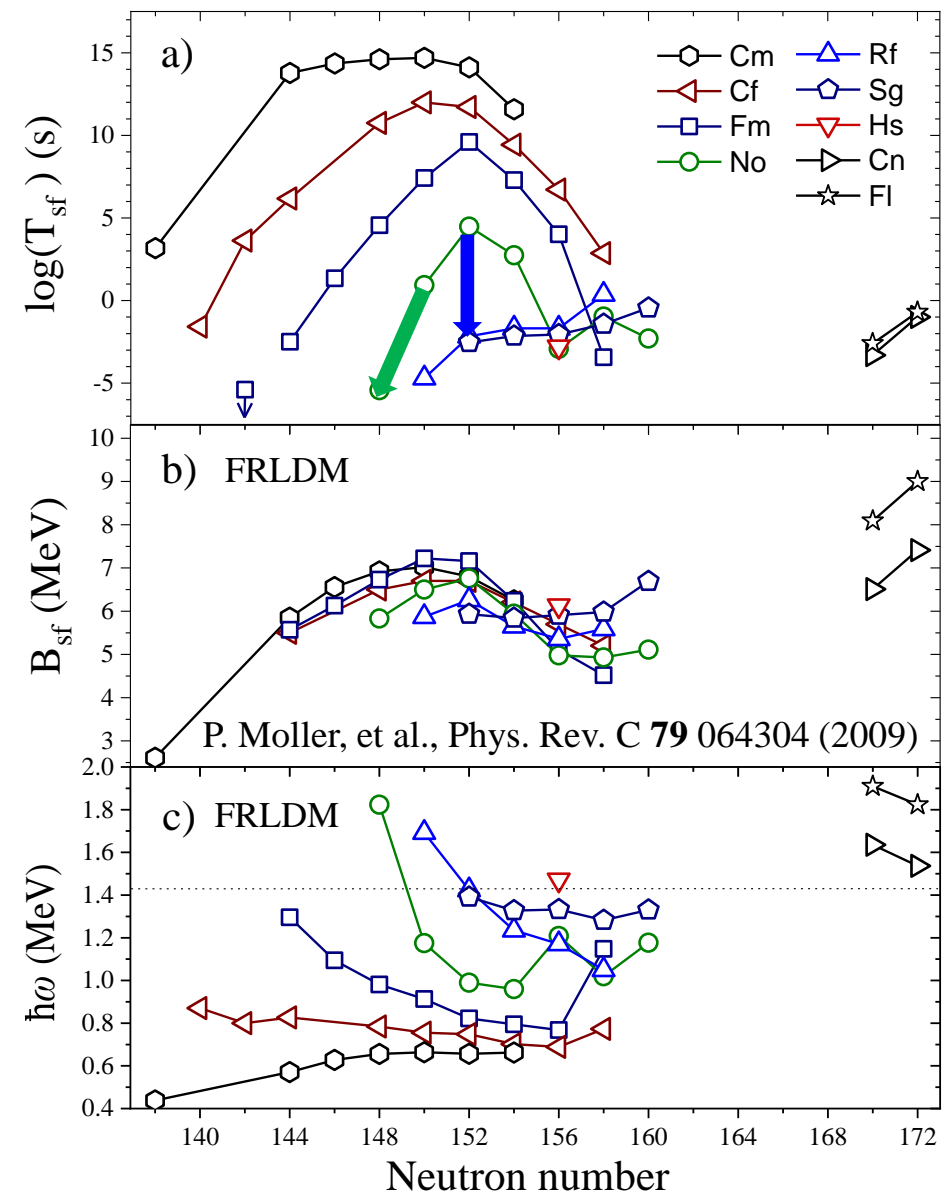
J. Khuyagbaatar, Nucl. Phys. A **1002**, 121958 (2020).



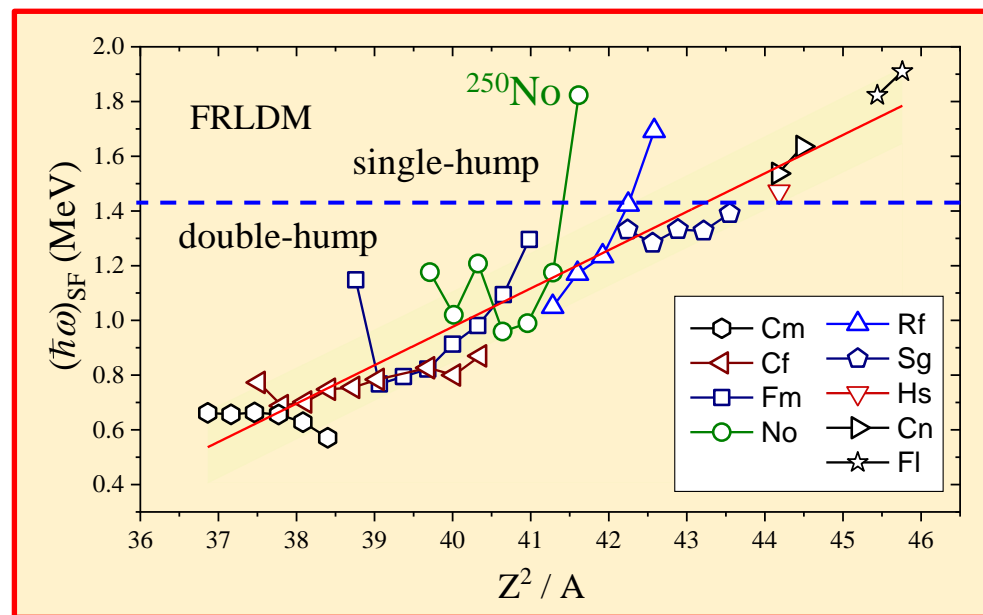
**Fission probability (parabolic-shaped barrier)**

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

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



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

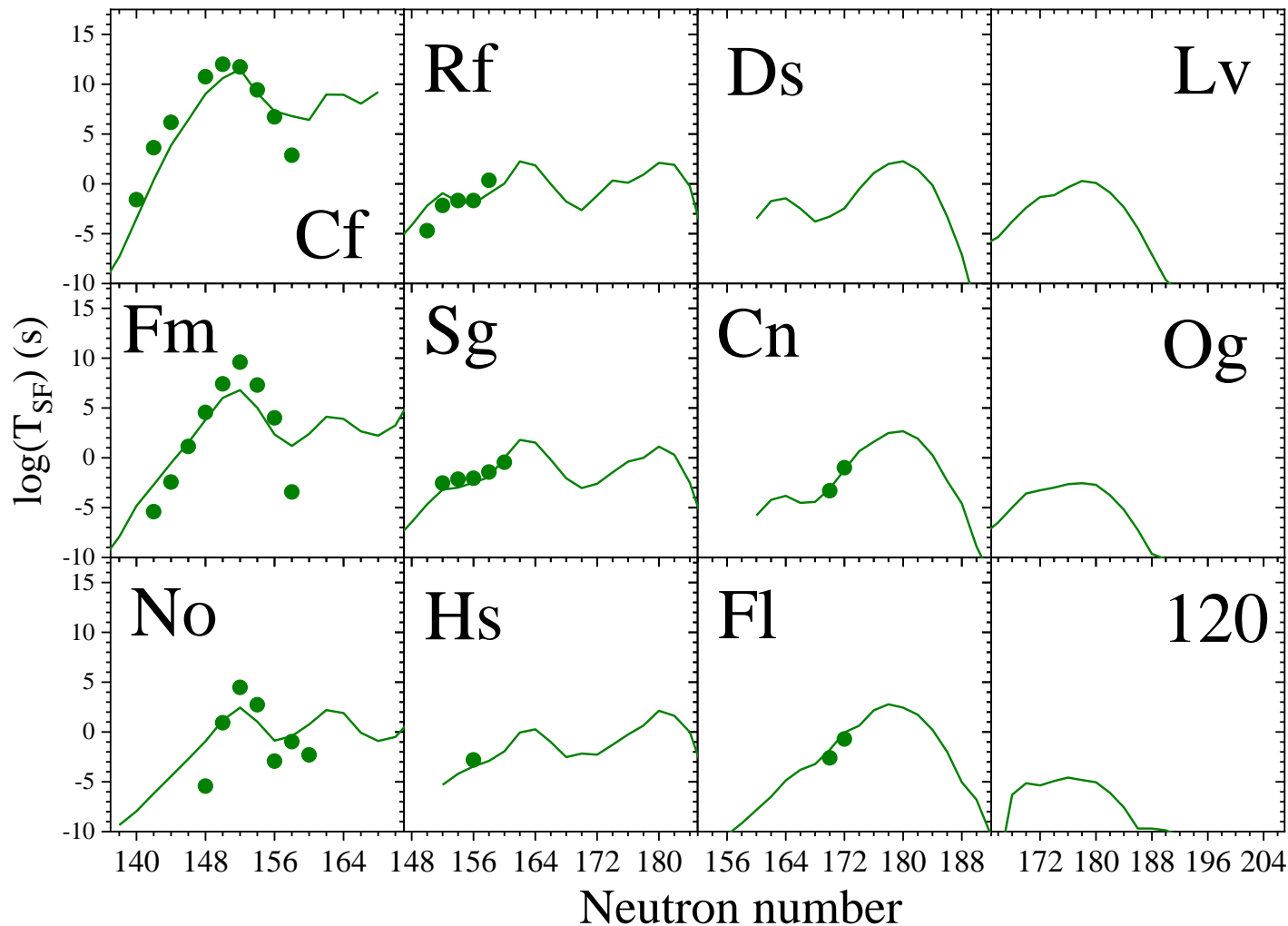


Outer barrier in  $^{256}\text{Rf}$  is below the first well.  
 S.G. Nilsson et al., Nucl. Phys. A **131**, 1 (1969)  
 J. Randrup et al., Nucl. Phys. A **217**, 221 (1973)  
 Yu.Ts. Oganessian et al., Nucl. Phys. A **239**, 157 (1975).

**SHN**  
**Narrow-shaped fission barrier !**

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.



**TASCA**, GSI

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

$^{282}\text{Cn}$ :  $T_{SF} \approx 1$  ms       $T_{SF}(\text{est.}) \approx 1$  ms

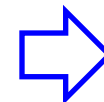
SHE-Factory, FLNR, JINR

Yu.Ts. Oganessian et al., Phys. Rev. C **108**, 024611 (2023)

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

Yu.Ts. Oganessian et al., Phys. Rev. C **112**, 014603 (2025)

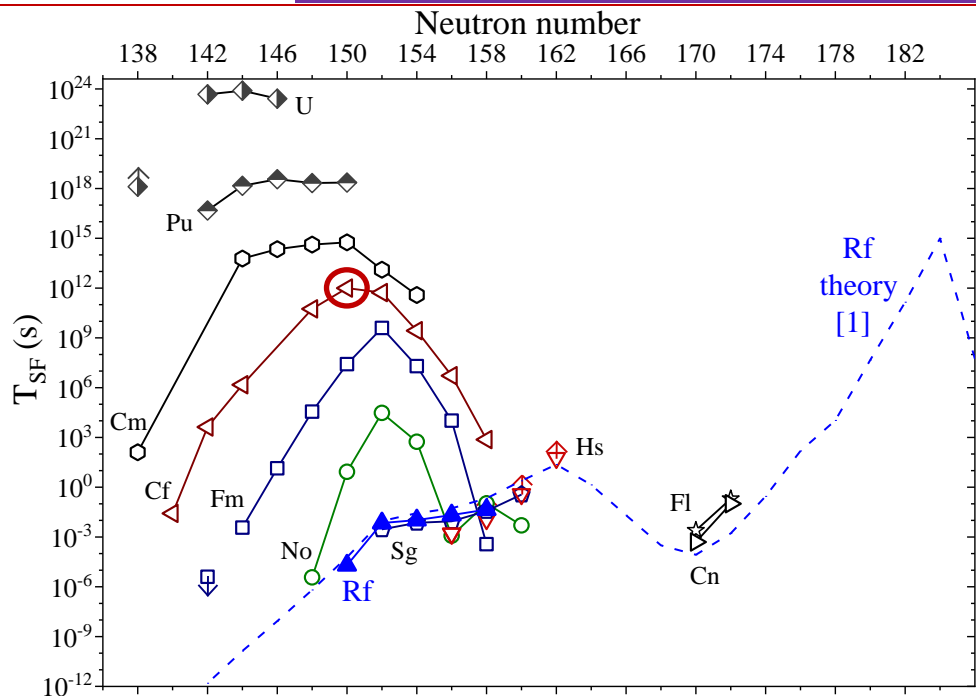
$^{280}\text{Cn}$ :  $T_{SF} \approx 10^{+18}_{-4}$   $\mu\text{s}$        $T_{SF}(\text{est.}) \approx 37$   $\mu\text{s}$



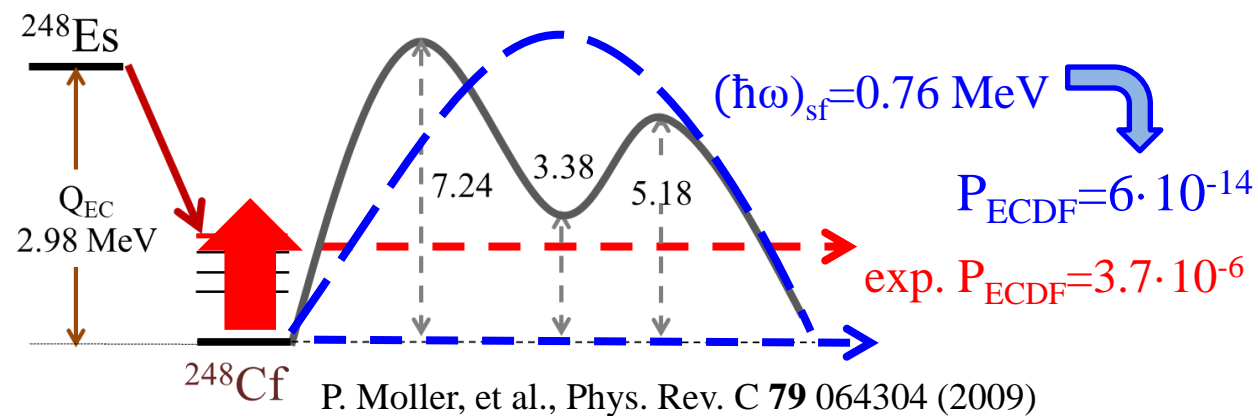
[The Nuclear Reaction Network WinNet](#)

Nucleosynthetic yields of a large variety of astrophysical environments and conditions.

M. Reichert et al., The Astrophysical Journal Supplement Series, **268**, 66 (2023)



## Electron-capture delayed fission (ECDF) [1]

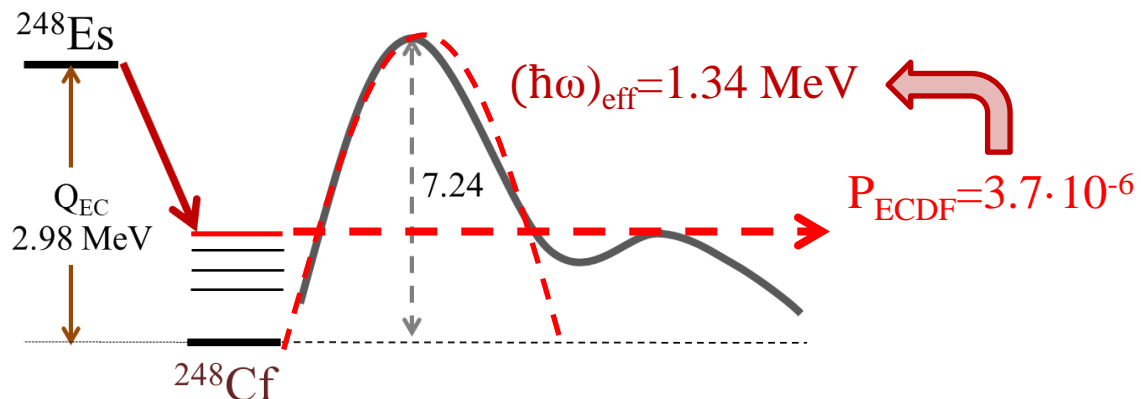


J. Khuyagbaatar, Eur. Phys. J. A **55**, 134 (2019).

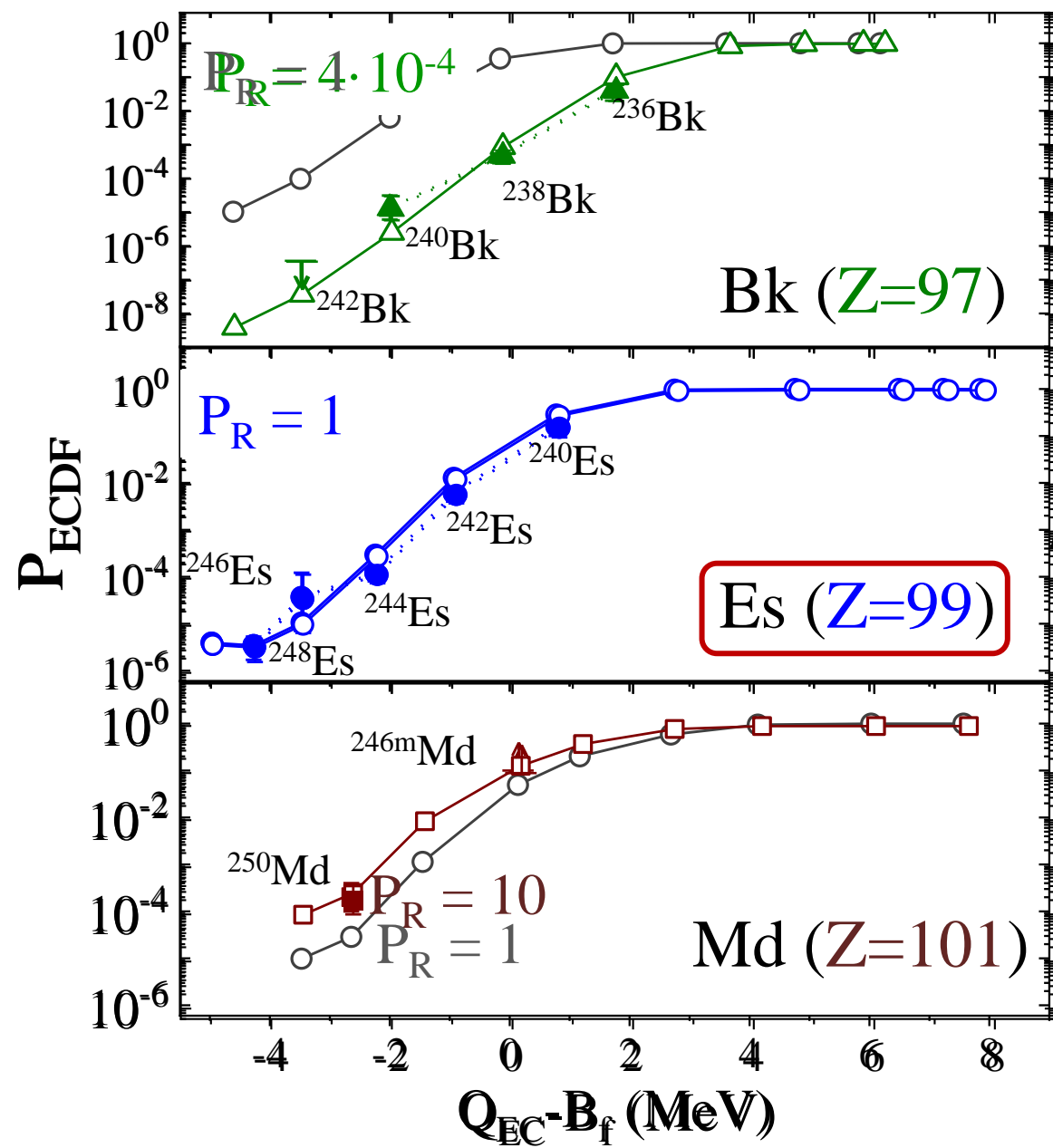
### Theoretical description of the ECDF:

#### ECDF with constant $\beta$ -strength function

H. L. Hall and D. C. Hoffman, Annu. Rev. Nucl. Part. Sci. **42**, 147 (1992).

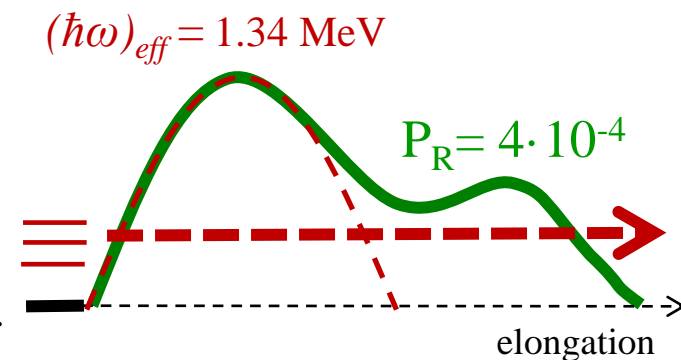


[1] A.N. Andreyev, et al., Rev. Mod. Phys. **85**, 1541 (2013).

J. Khuyagbaatar, Eur. Phys. J. A **55**, 134 (2019).


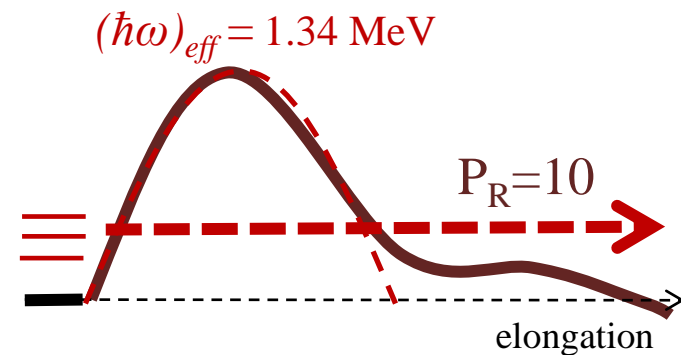
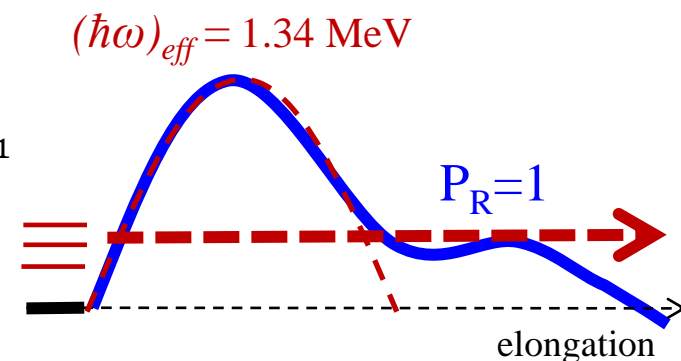
$$P_f \approx \left[ 1 + \exp\left(\frac{2\pi(B_f - E)}{\hbar\omega_{eff}}\right) \right]^{-1}$$

A variation in the barrier shape as a function of  $Z$  was not accounted for.

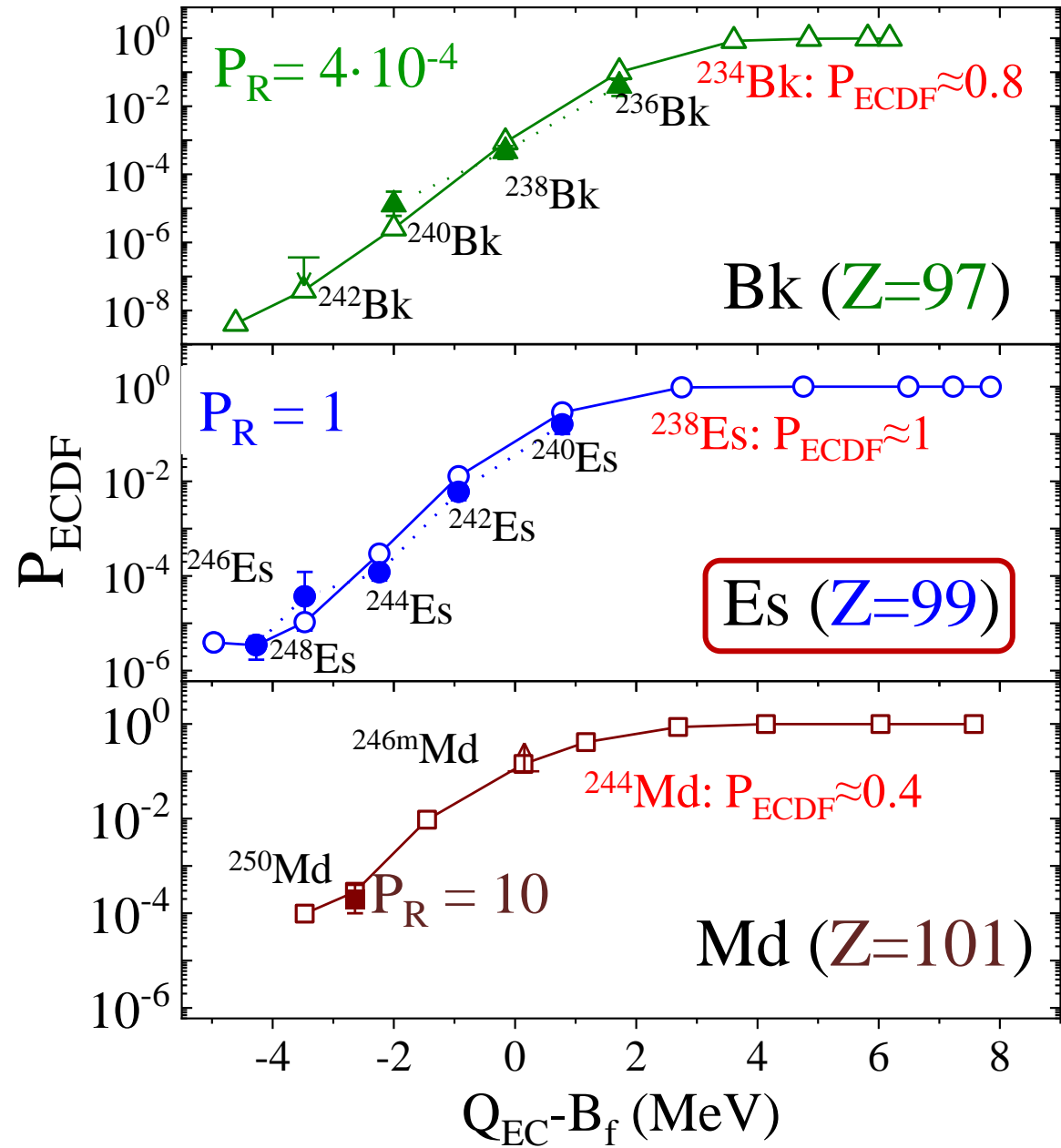


$$P_f \approx P_R \left[ 1 + \exp\left(\frac{2\pi(B_f - E)}{\hbar\omega_{eff}}\right) \right]^{-1}$$

$P_R \sim$  correction factor for the transmission coefficient  $\sim$  accounts a deviation of the real barrier shape from the parabola.



J. Khuyagbaatar, Eur. Phys. J. A **55**, 134 (2019).



$^{234}\text{Bk}$ :

D. Kaji, et al.,  
J. Phys. Soc. Jpn. **85**, 015002 (2016)

$^{242}\text{Es}$

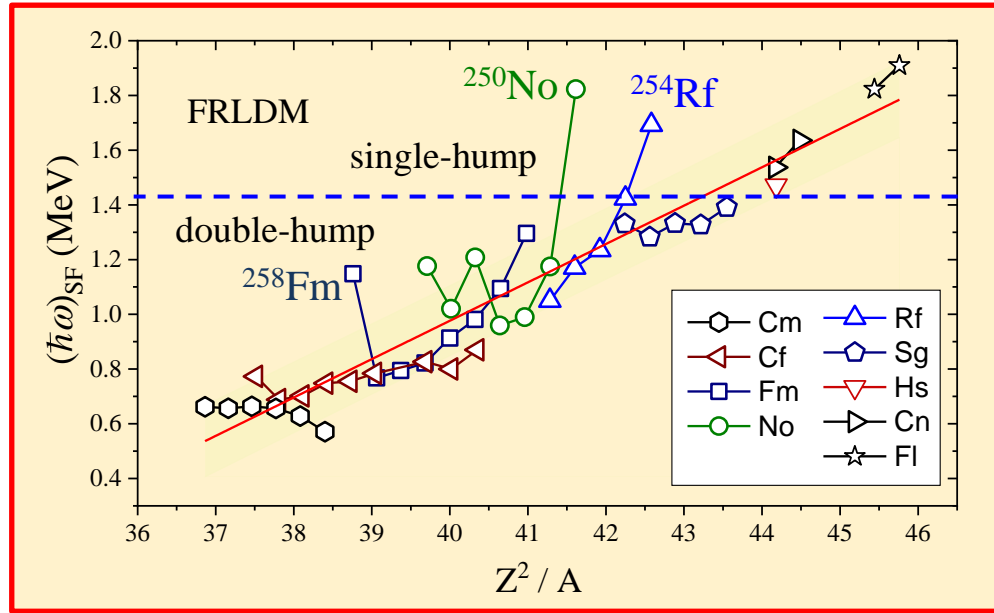
J. Khuyagbaatar et al.,  
Phys. Rev. C **109**, 034311 (2024)

Search for hitherto unknown  $^{238}\text{Es}$   
Sep. 2025 @RITU, JYFL  
data are under evaluation

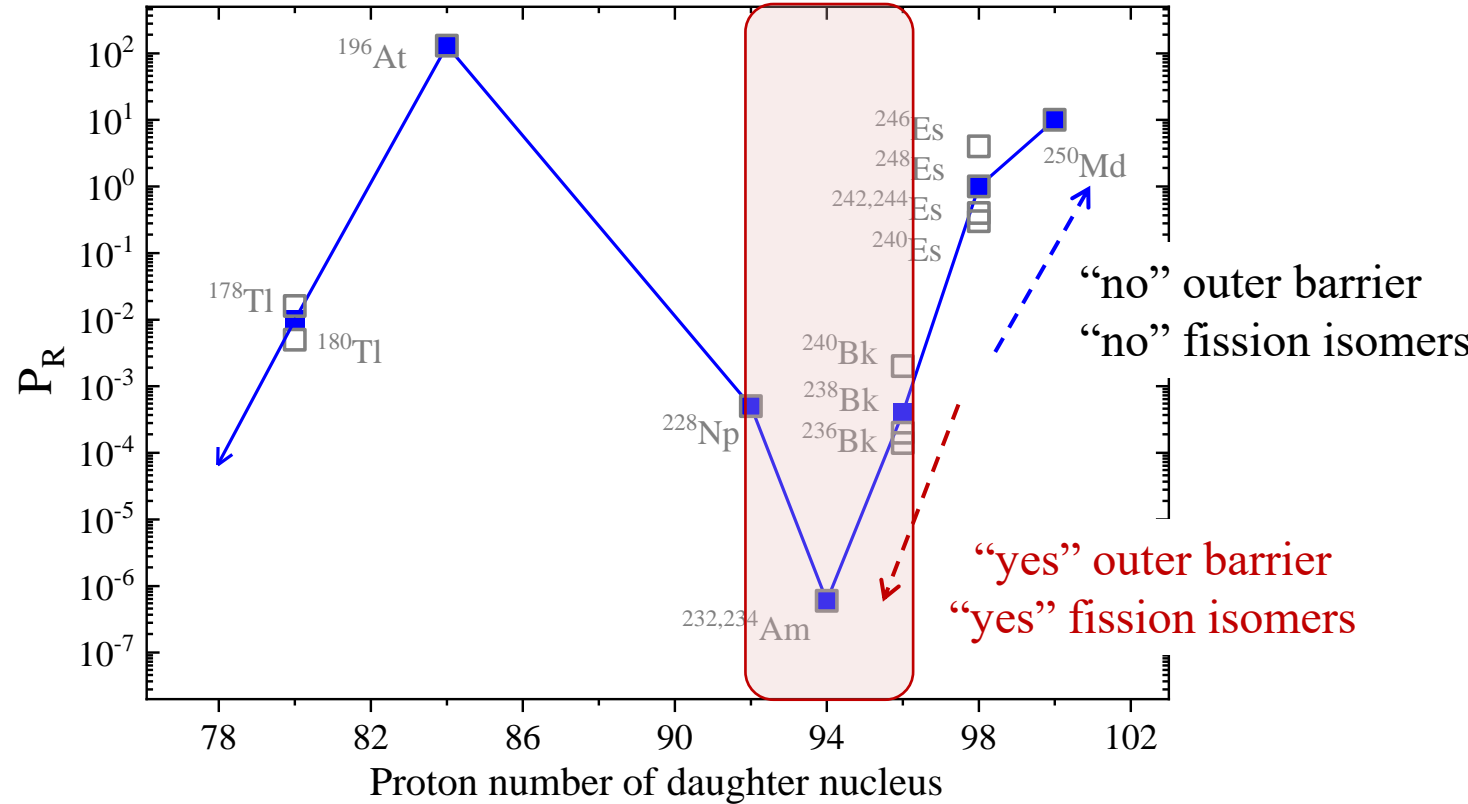
$^{244}\text{Md}$

J. Khuyagbaatar et al.,  
Phys. Rev. Lett. **125** 142504 (2020)  
EC was not observed

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



J. Khuyagbaatar, Eur. Phys. J. A **55**, 134 (2019).

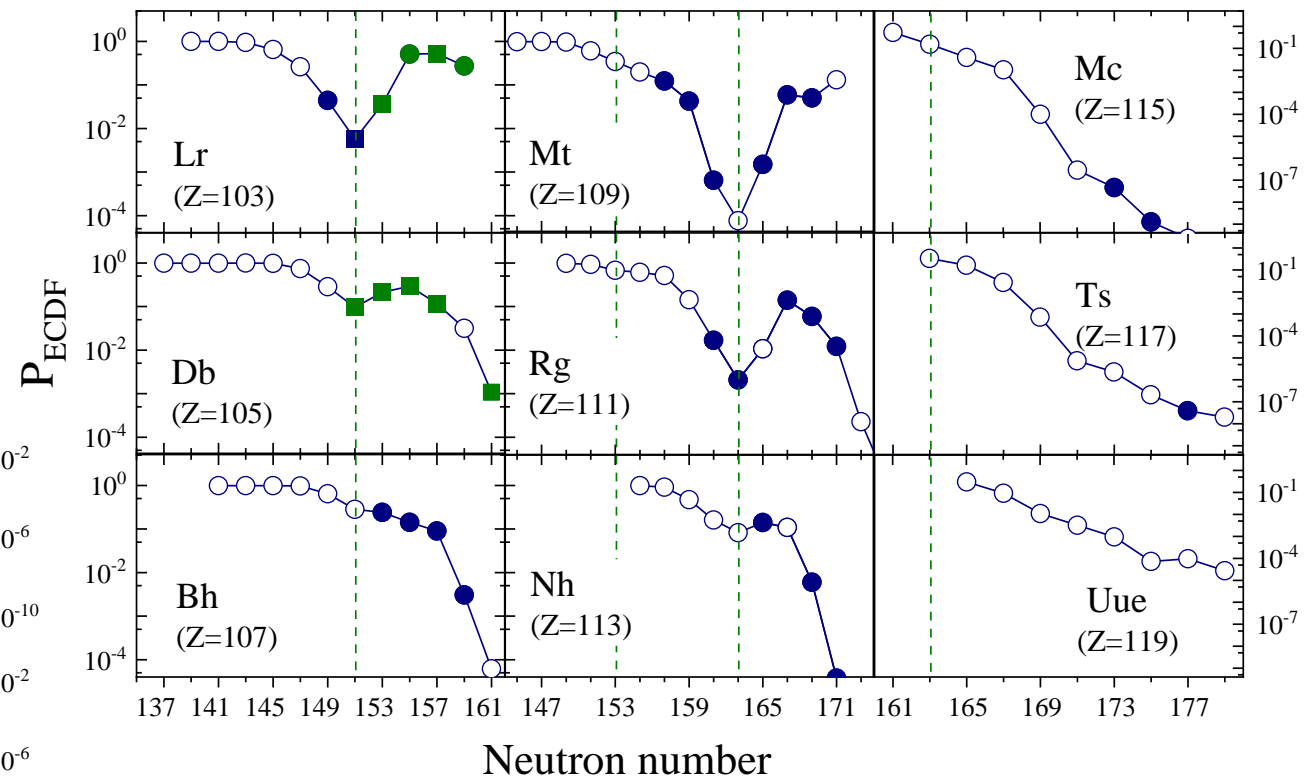
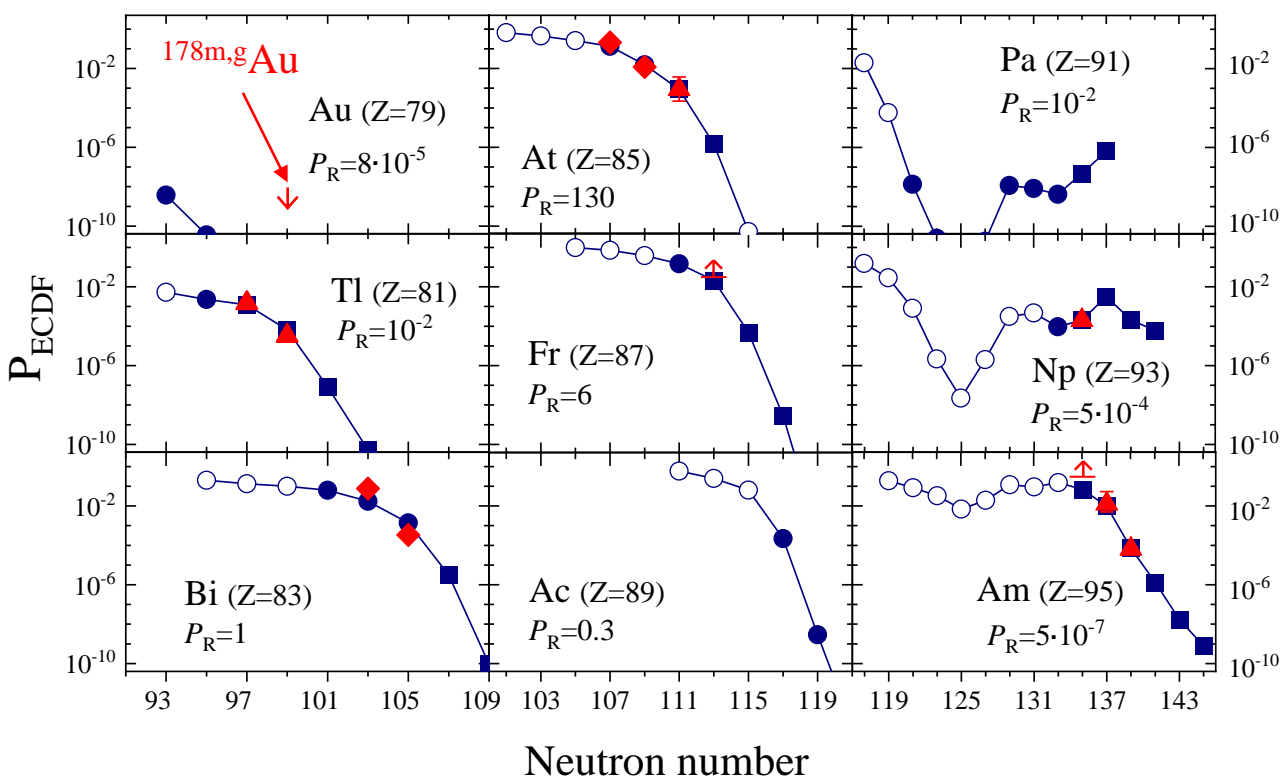


**SHN**  
**Narrow-shaped fission barrier !**

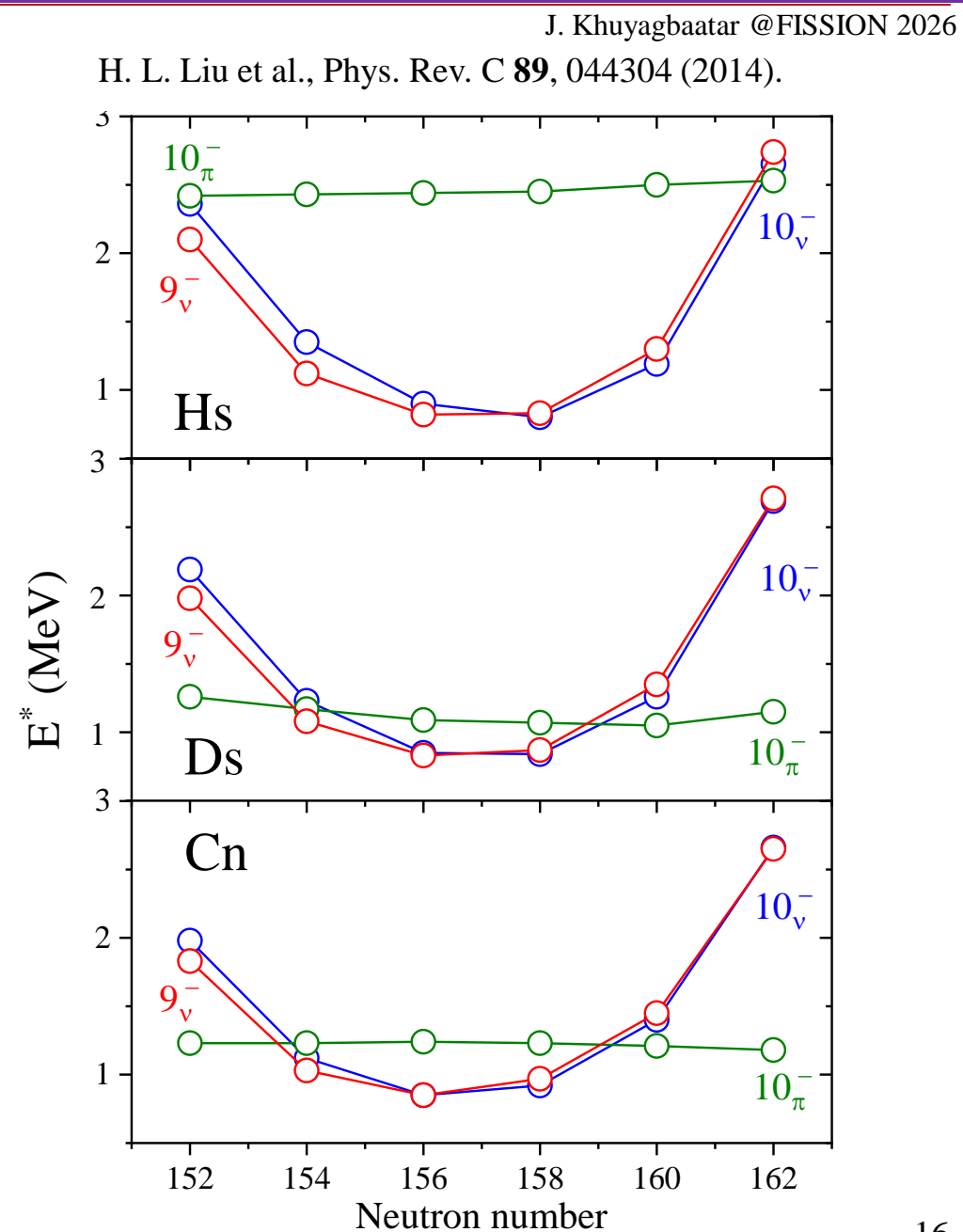
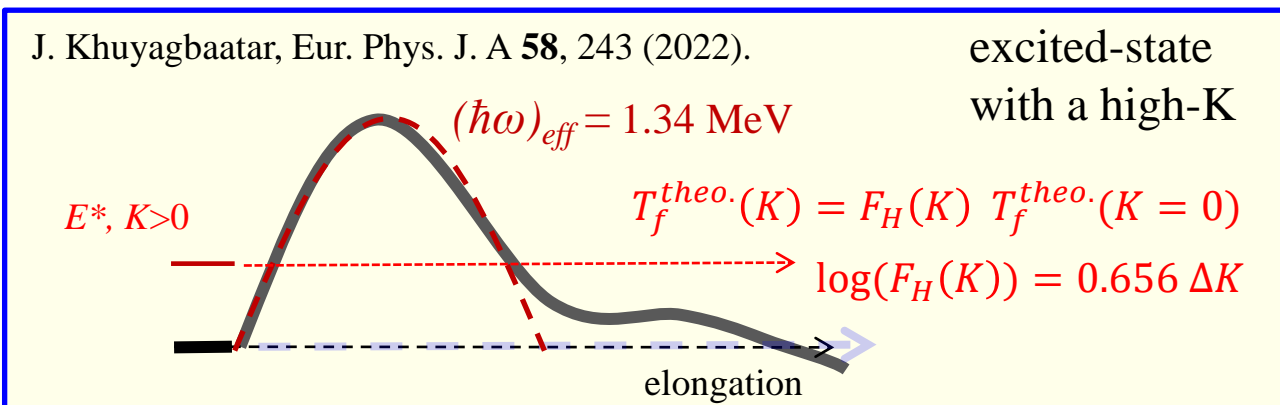
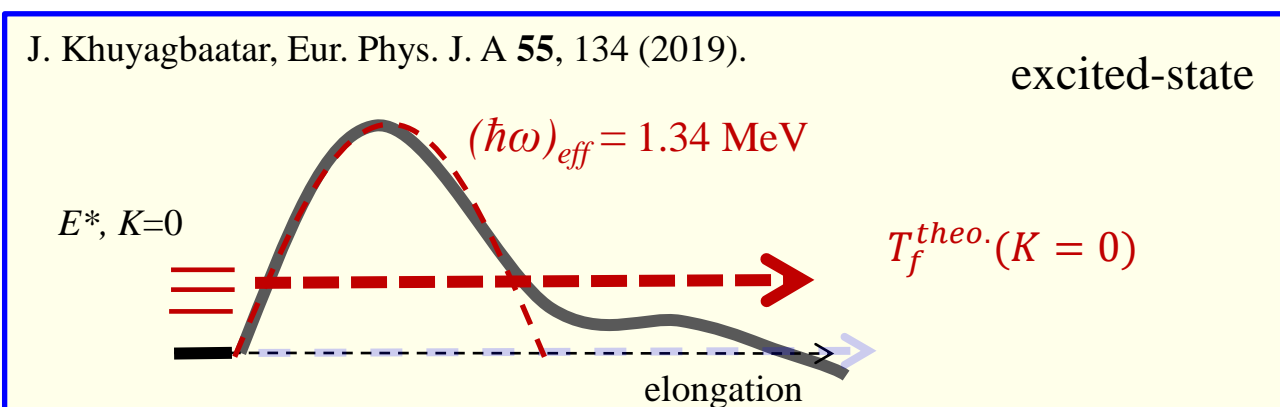
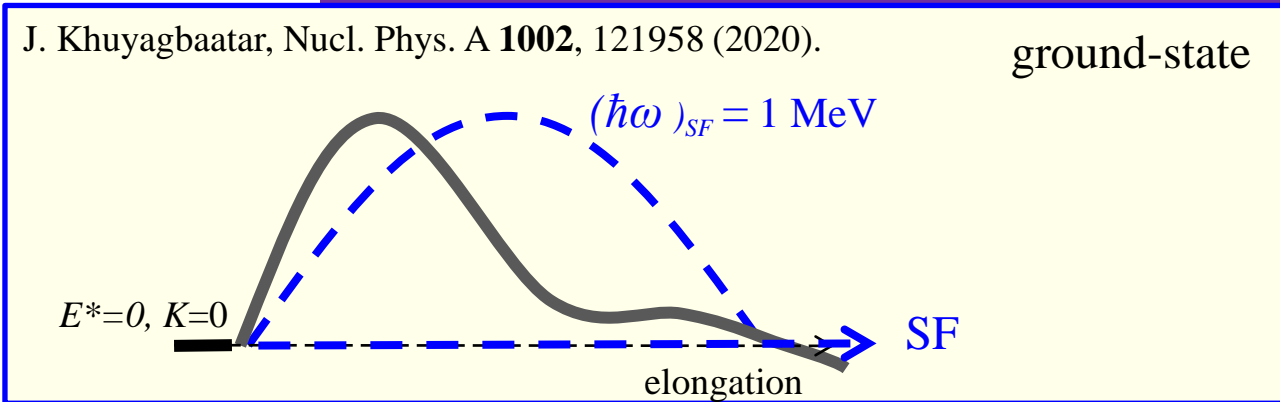


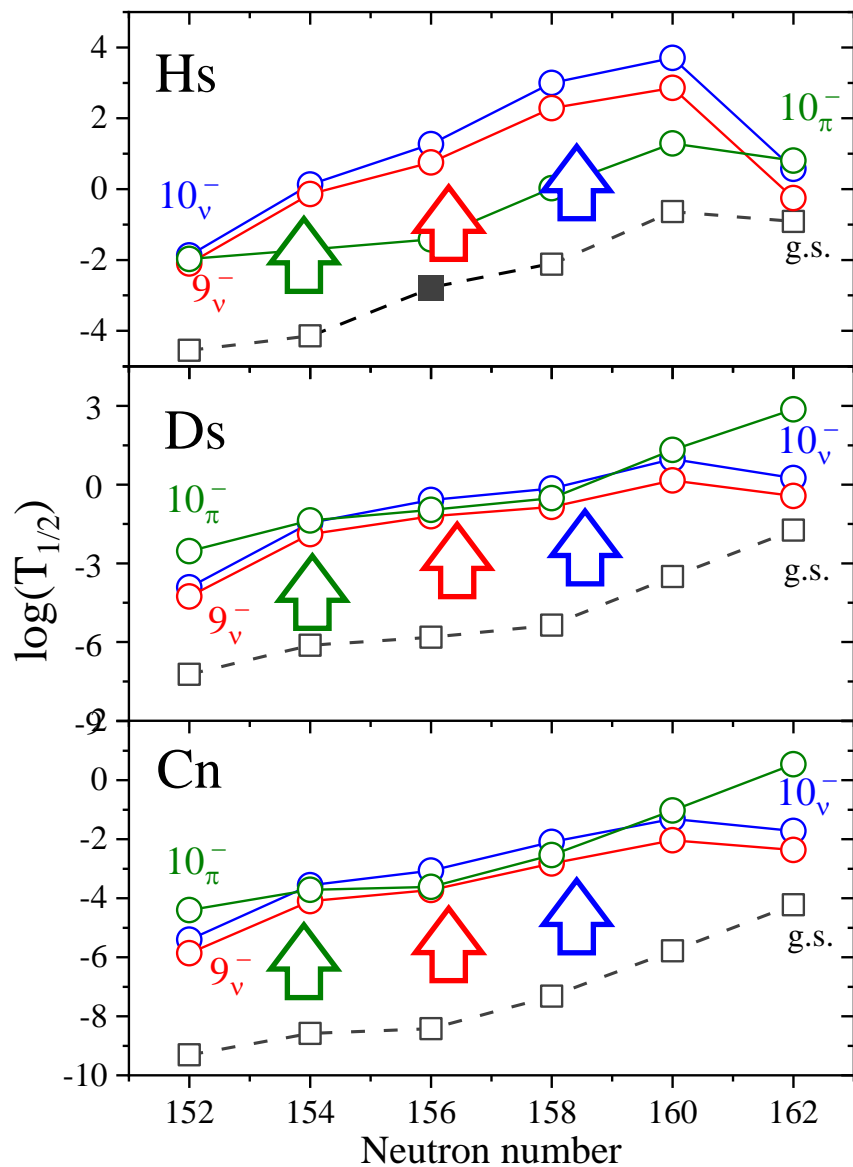
**SHN**  
**"No" outer barrier**

Very recent data on  $P_{\text{ECDF}}$  for  $^{178\text{m}}\text{Au}$  and  $^{178\text{g}}\text{Au}$   
 B. Andel et al., Phys. Rev. C 113, 014325 (2026)

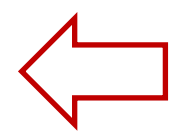


ECDF is the one of the main decay mode of neutron-deficient (neutron-rich) superheavy nuclei, if EC ( $\beta^-$ ) takes place.

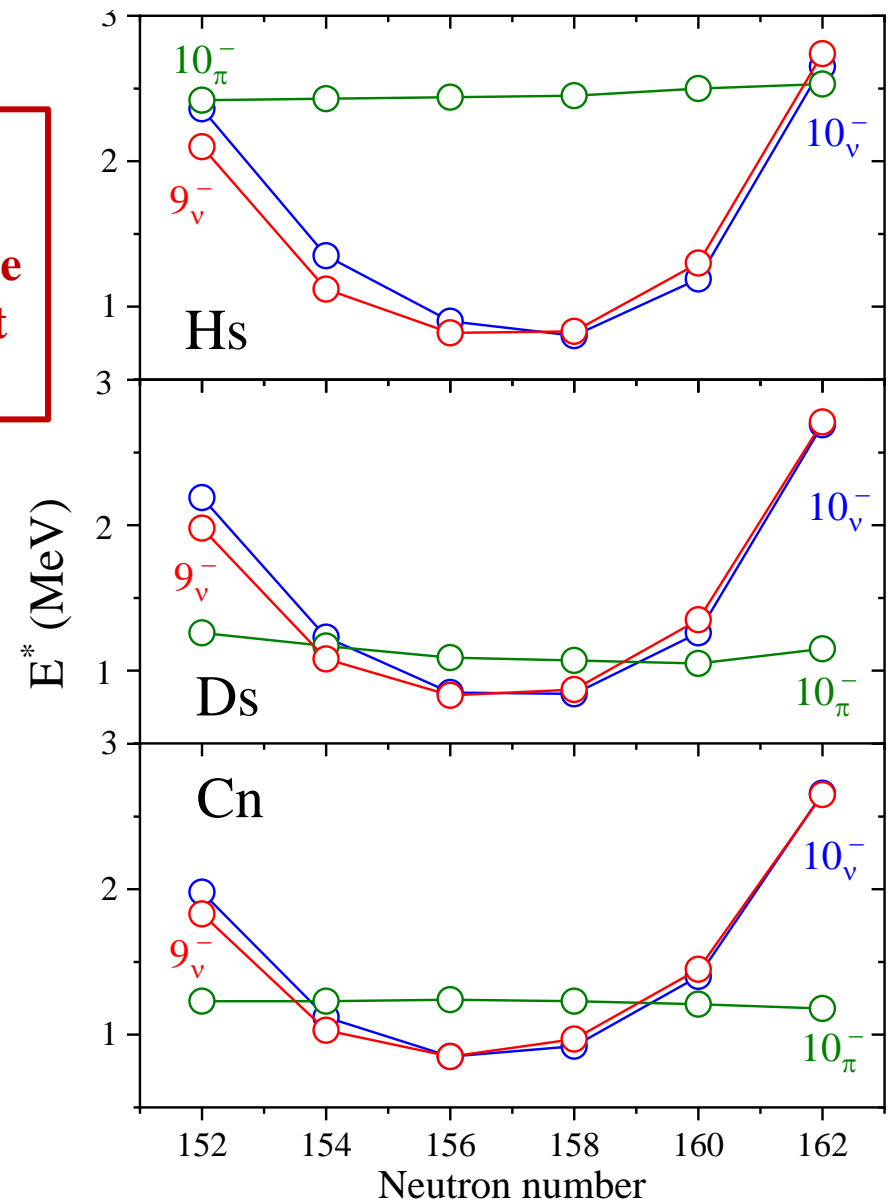




**SHN**  
Excited states with high-K are most stable configuration against the fission!



**Clouds of stability**



Clouds of stability (K-isomeric state)  
VS  
sea of instability (ground state)

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

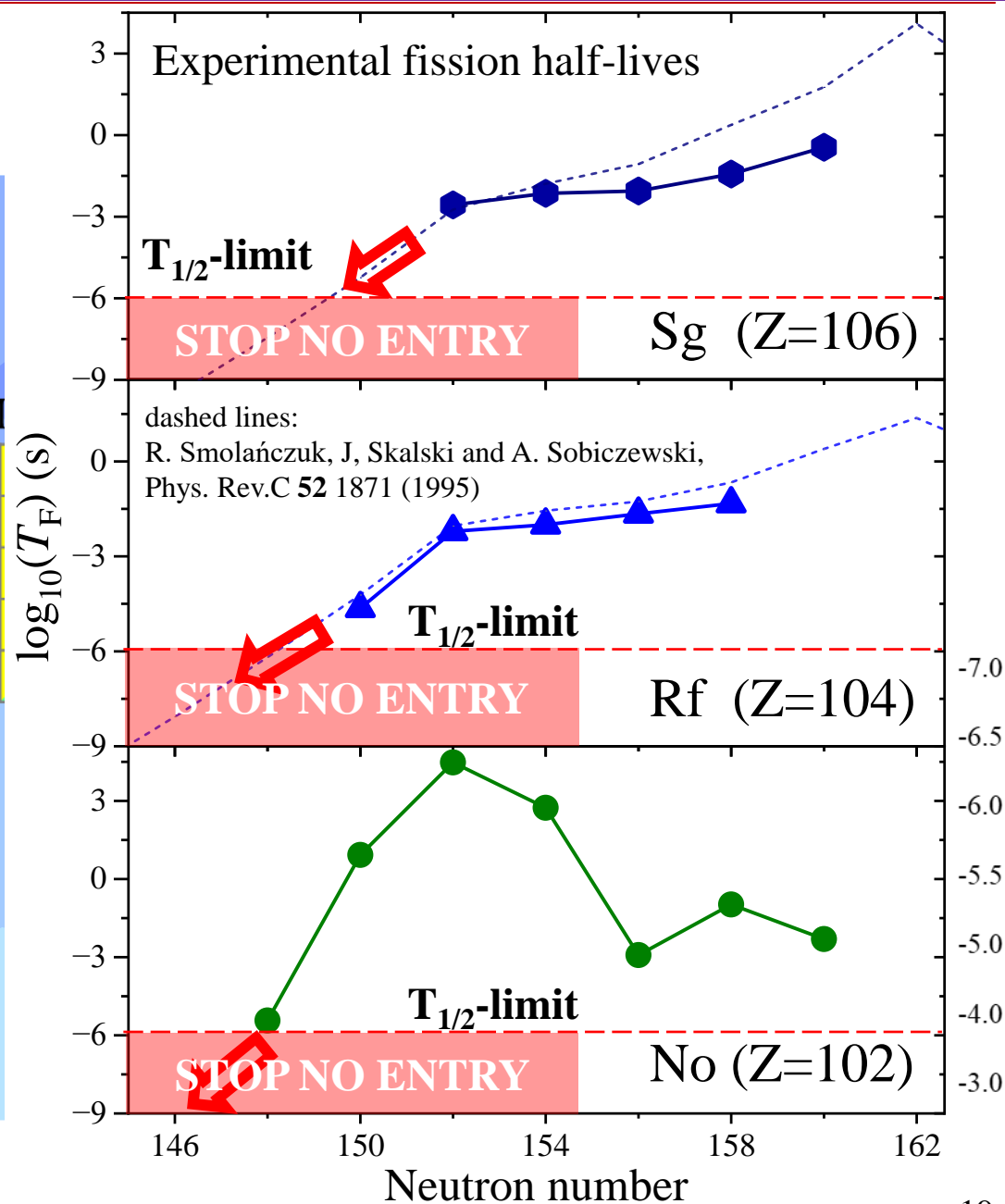
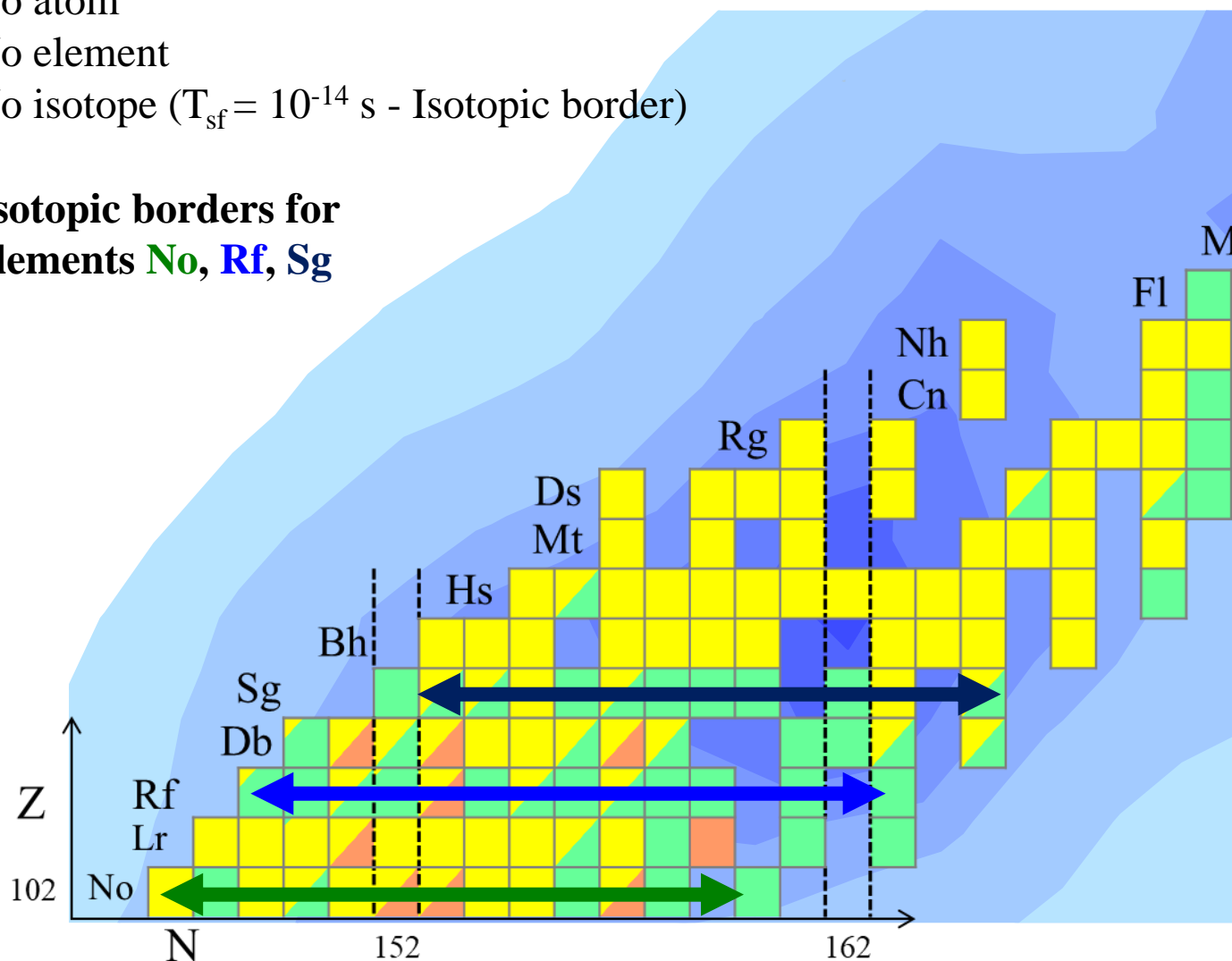
No electron shell

No atom

No element

No isotope ( $T_{sf} = 10^{-14}$  s - Isotopic border)

Isotopic borders for elements **No**, **Rf**, **Sg**



## Experiment:

F. Kondev, G. Dracoulis and T. Kibedi, ADNDT, 103-104, 50 (2015)  
 P. M. Walker and F. G. Kondev, EPJ. ST.233, 983 (2024)  
 K. Kessaci, et al., PRC 110, 054310 (2024).

## Theory:

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).  
 P. Jachimowicz, M. Kowal and J. Skalski, Phys. Rev. C **92**, 044306 (2015).

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

### $^{270}\text{Ds}$ ( $\approx 20$ times longer)

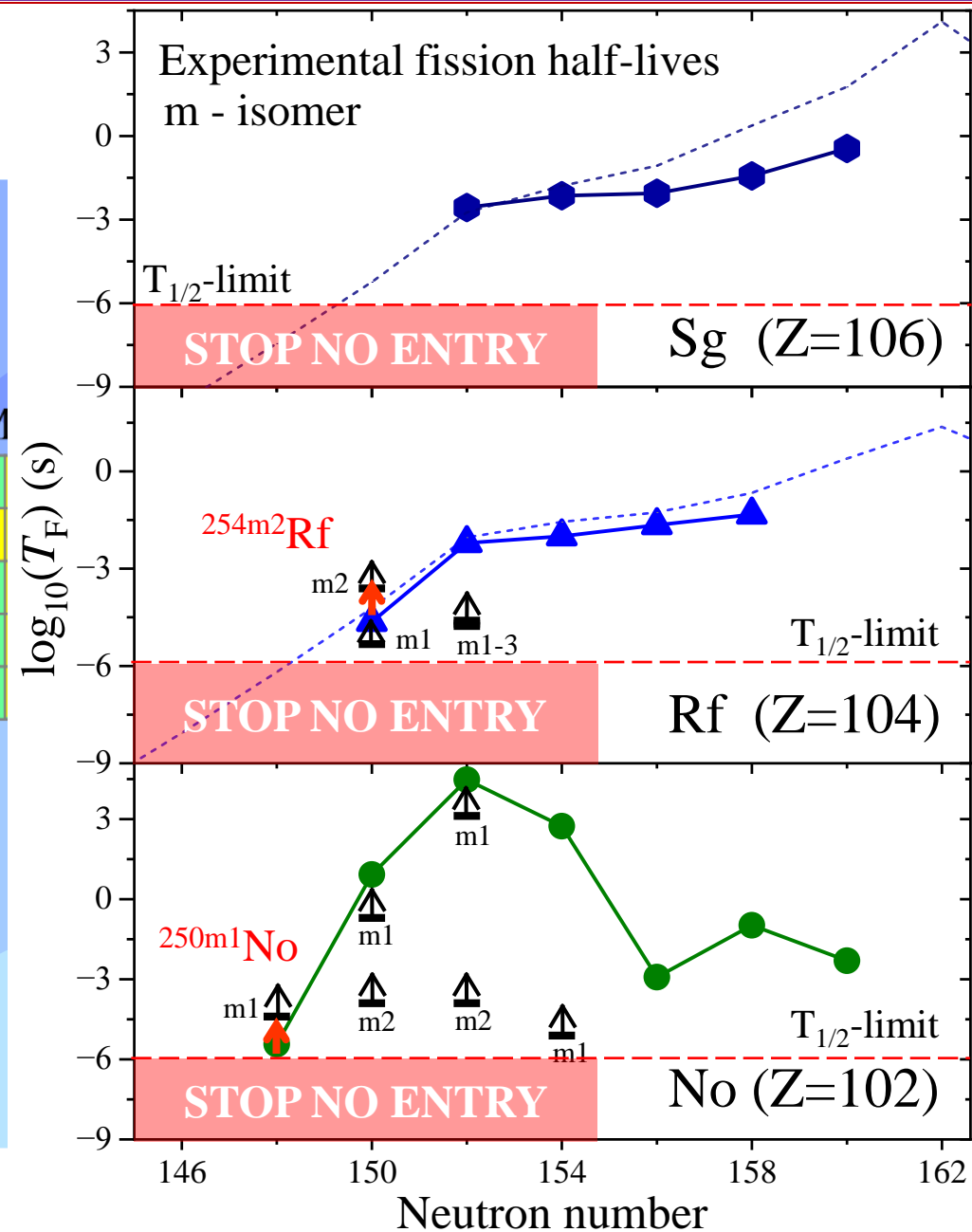
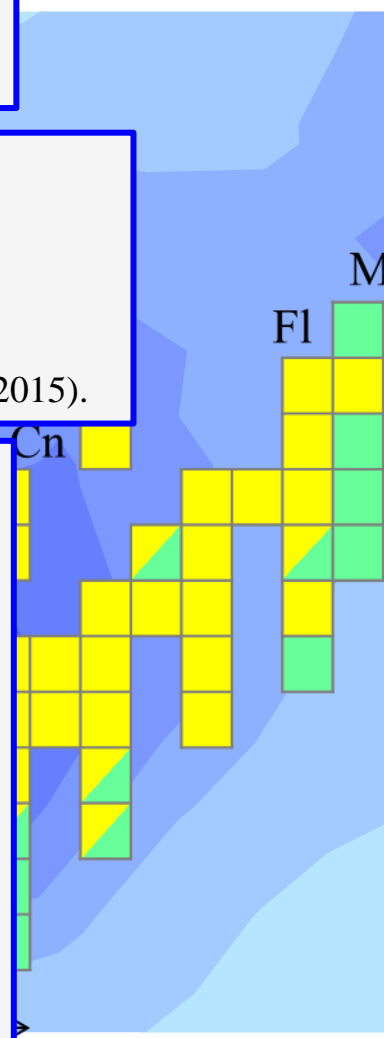
S. Hofmann et al., Eur. Phys. J. A **10**, 5 (2001).

### $^{250}\text{No}$ ( $\approx 10$ times longer)

A. V. Belozеров 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).

### $^{254}\text{Rf}$ ( $\approx 10$ times longer)

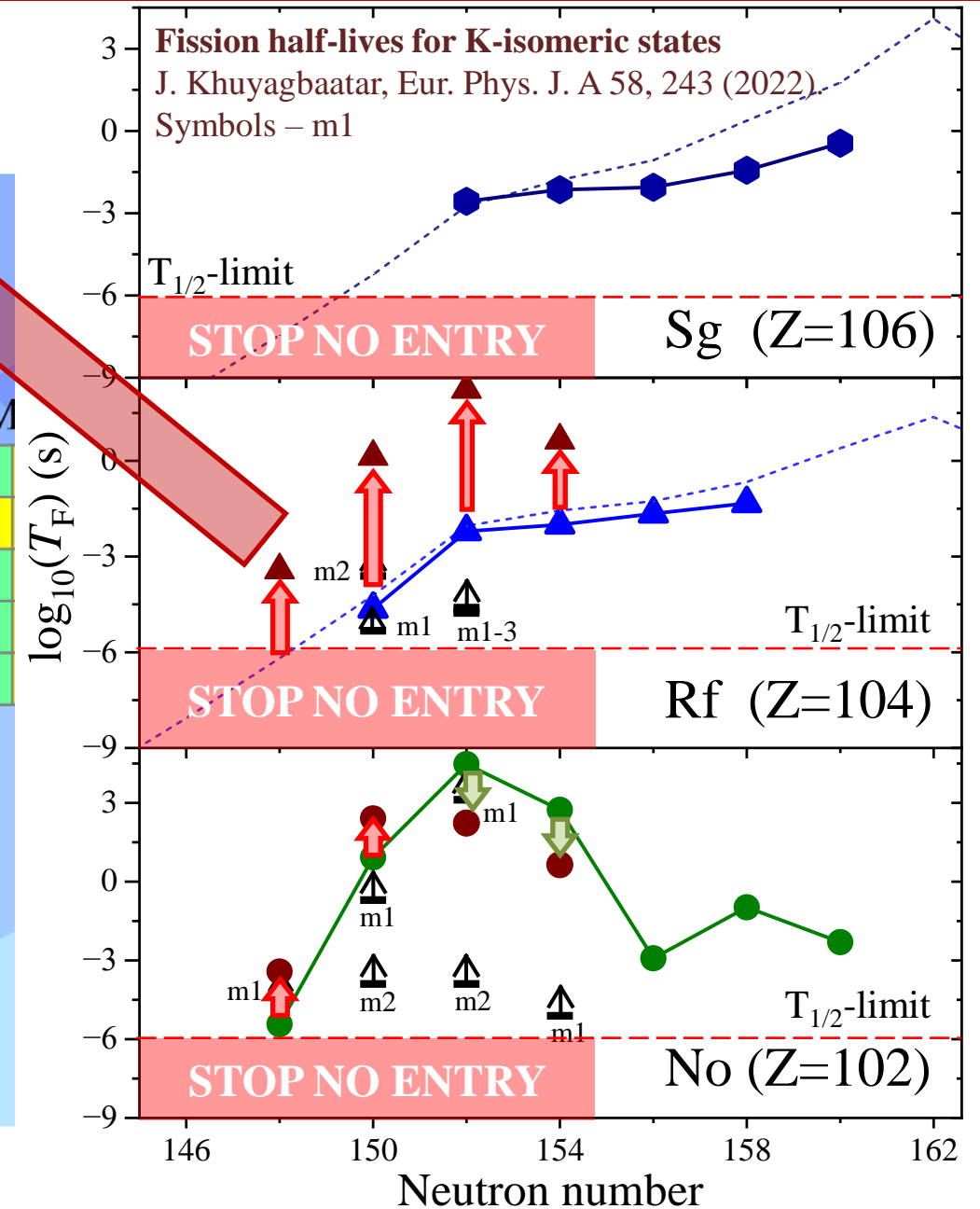
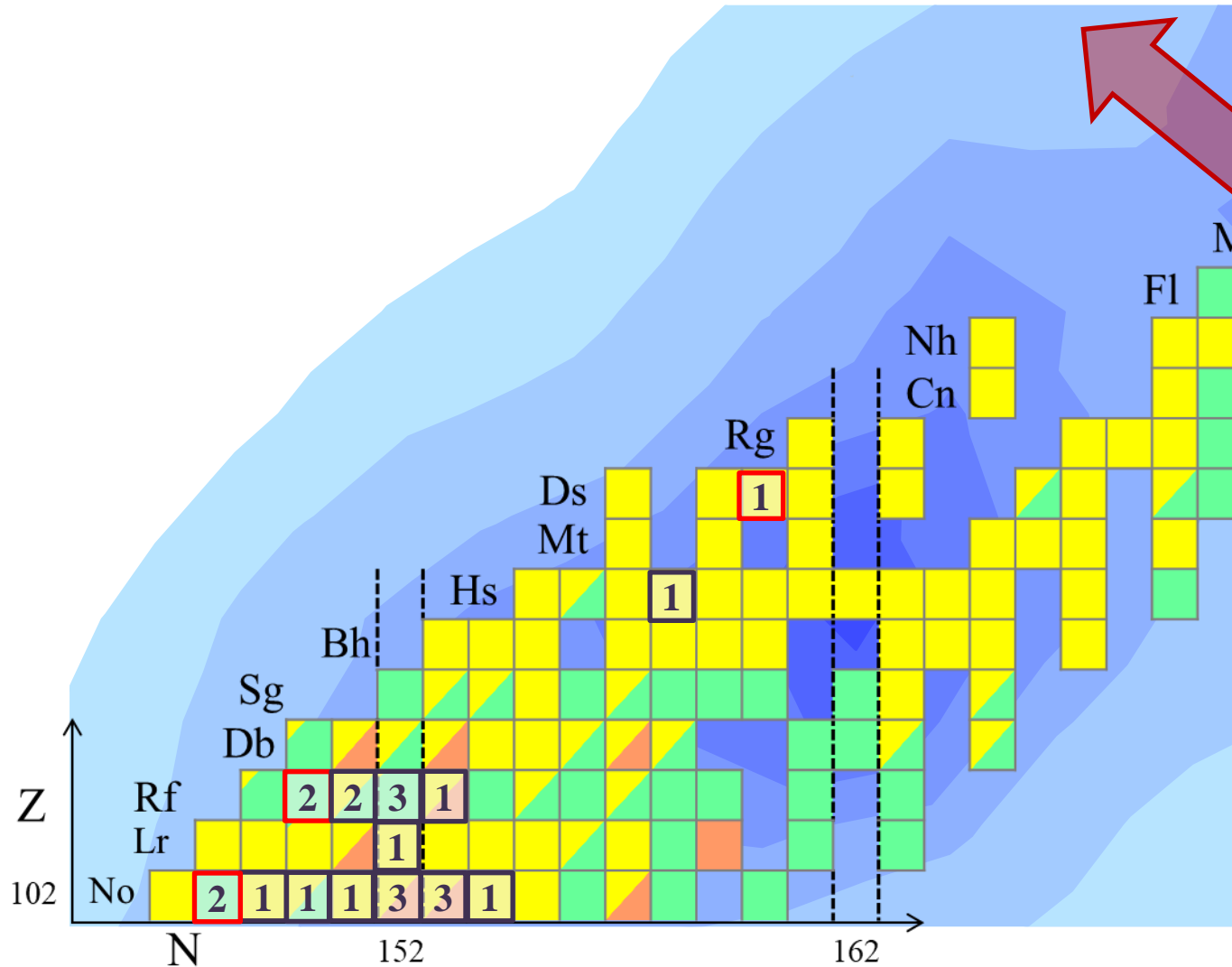
H. M. David et al., Phys. Rev. Lett. **115**, 132502 (2015).



# Fission half-lives of K-isomeric states in SHN: prediction

**$^{252}\text{Rf}$ :  $T_{\text{SF}} \approx 100$  ns**

J. Khuyagbaatar et al., Phys. Rev. C. **104**, L031303 (2021)

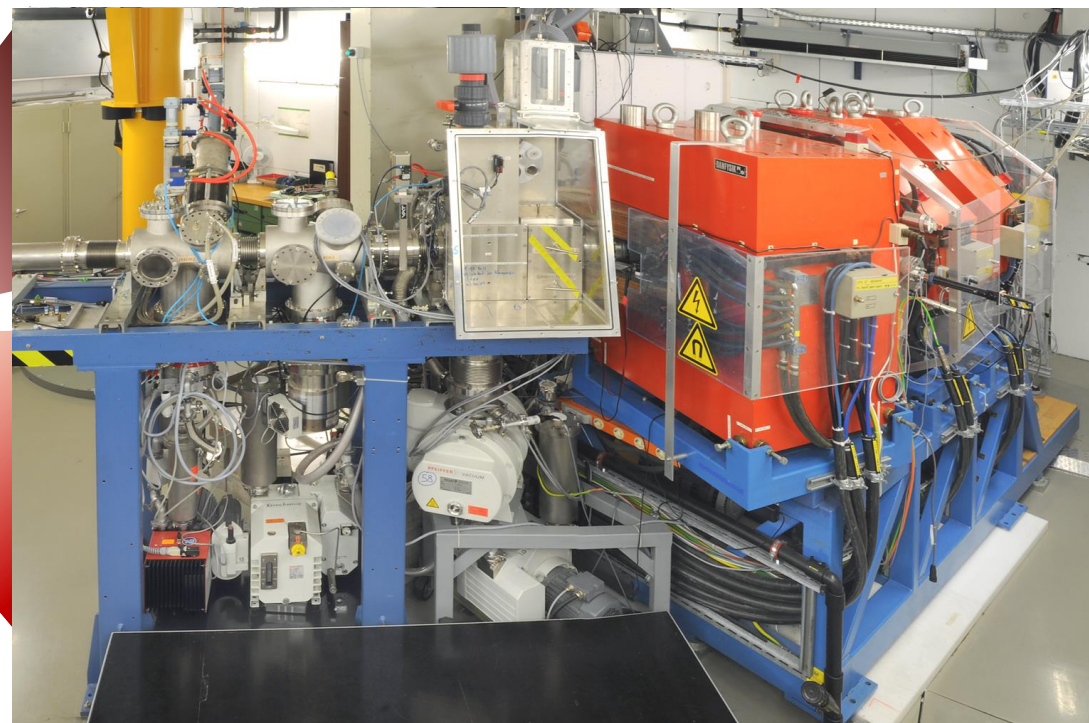
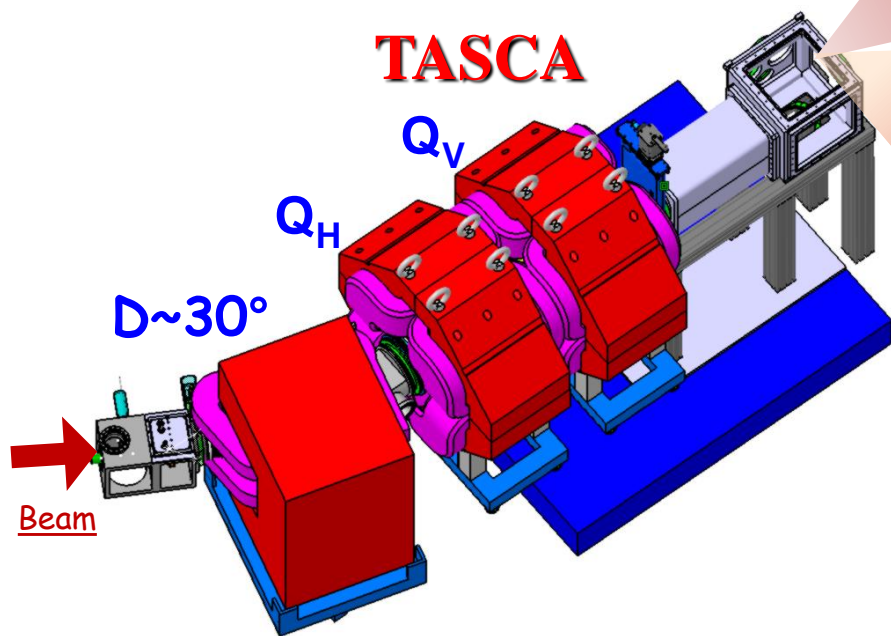


# Experiment

## TransActinide Separator and Chemistry Apparatus



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



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

J. Khuyagbaatar *et al.*,  
Nucl. Inst. A **689**, 40 (2012)  
Phys. Rev. A **88**, 042703 (2013)

## TransActinide Separator and Chemistry Apparatus

### Confirmation of the element 117 and discovery of <sup>270</sup>Db

J. Khuyagbaatar et al., Phys. Rev. Lett. **112** 172501 (2014)

### Safe identification of SHN

J. Khuyagbaatar et al., Phys. Rev. C **99**, 054306 (2019)

### Safe search for elements beyond Og (119 and 120 elements)

J. Khuyagbaatar et al., Phys. Rev. C **102**, 064602 (2020)

### Chemistry studies of Fl

A. Yakushev et al., Front. Chem. **10**, 976635 (2022)

### Chemistry studies of Nh/Mc

A. Yakushev et al., Front. Chem. **12**, 1474820 (2024)

### Examining the robustness of N=126 shell and discovery of <sup>221</sup>U

J. Khuyagbaatar et al., Phys. Rev. Lett. **115**, 242502 (2015)

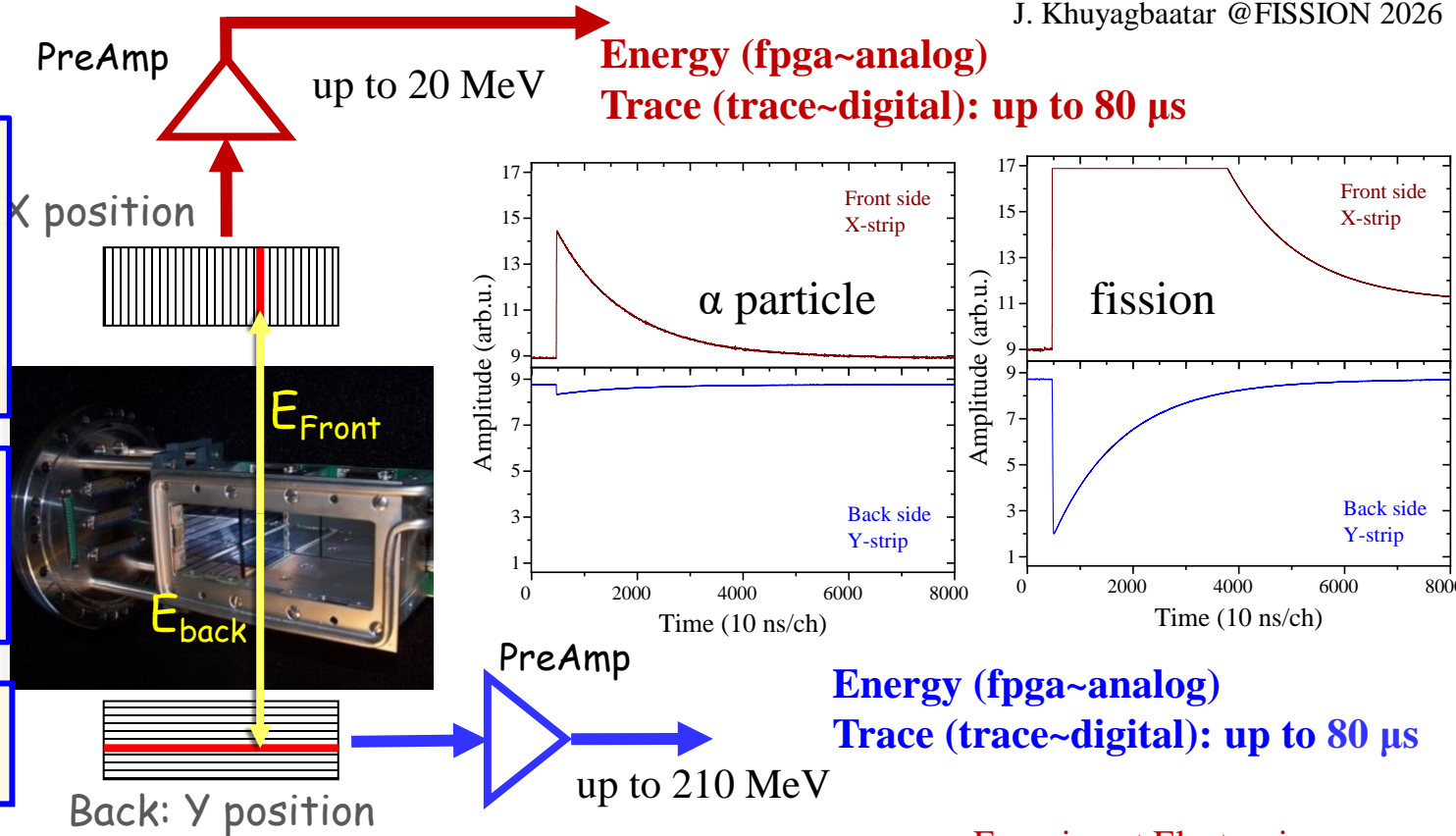
### Nuclear reaction studies: non-fusion reaction products

A. Di Nitto et al., Phys. Lett. B **784**, 199 (2018)

### Isomer studies via a triggerless measurement of conversion electrons (2012)

J. Khuyagbaatar et al., Nucl. Phys. A. **994**, 121662 (2020)

Phys. Rev. C **103**, 064303 (2021)

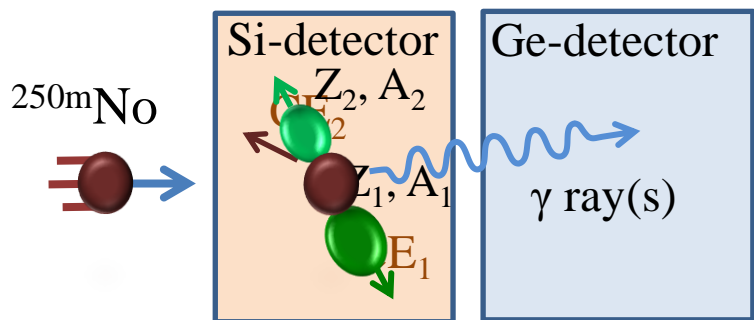


Experiment Electronics Department, GSI



N. Kurz et al., GSI Scientific Report 252 (2012)  
 J. Hoffmann et al., GSI Scientific Report 253 (2012)  
 J. Khuyagbaatar et al., GSI Scientific Report 212 (2012)

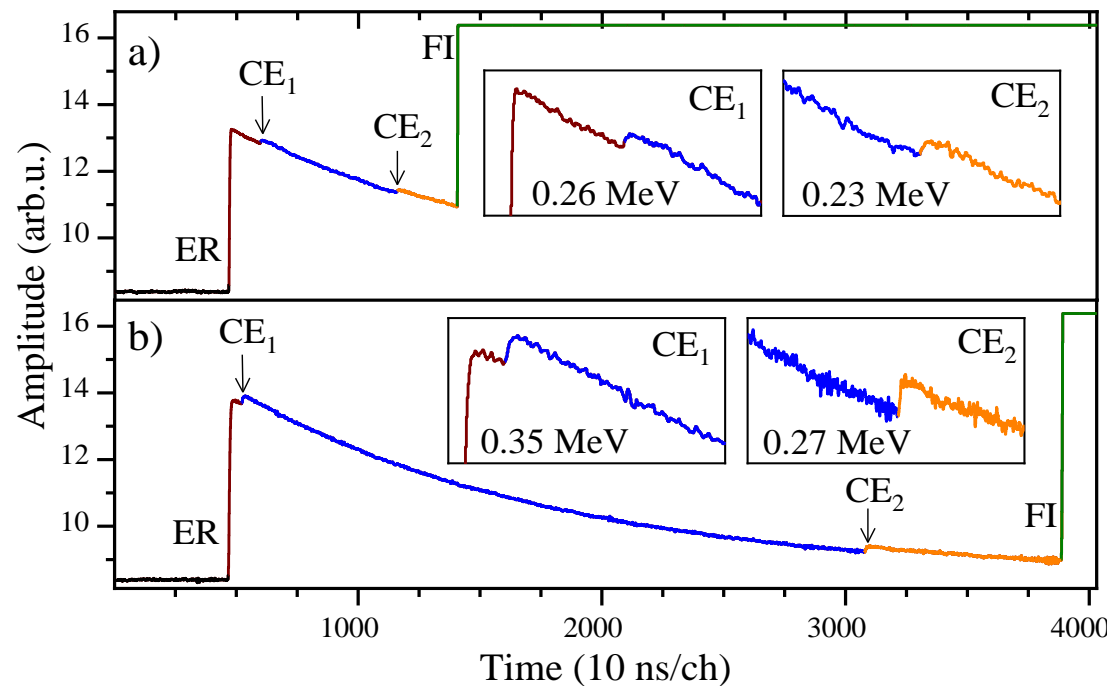
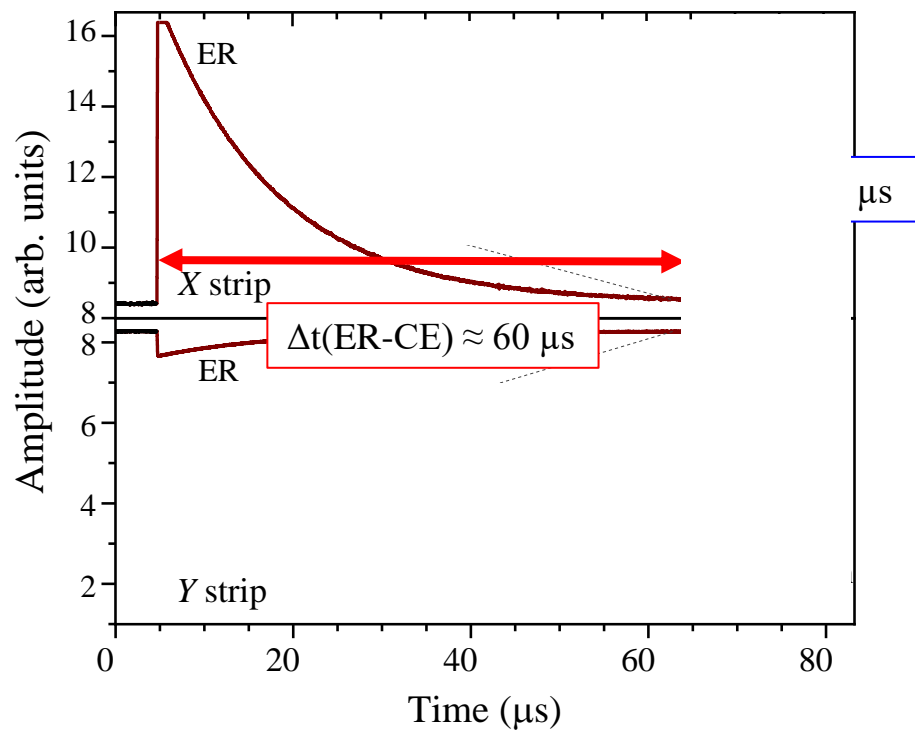
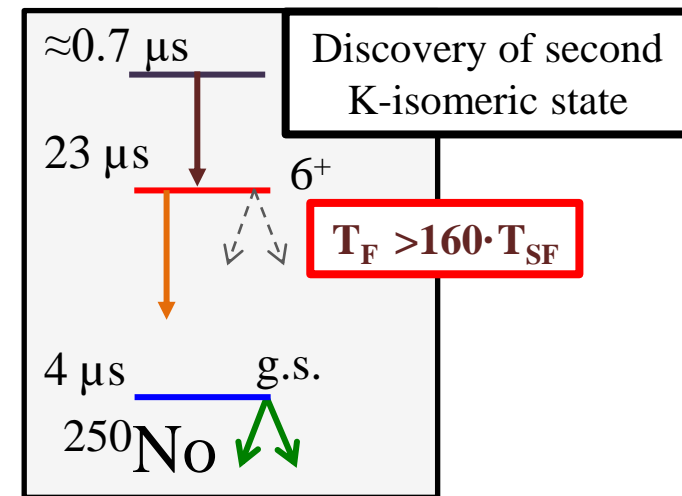
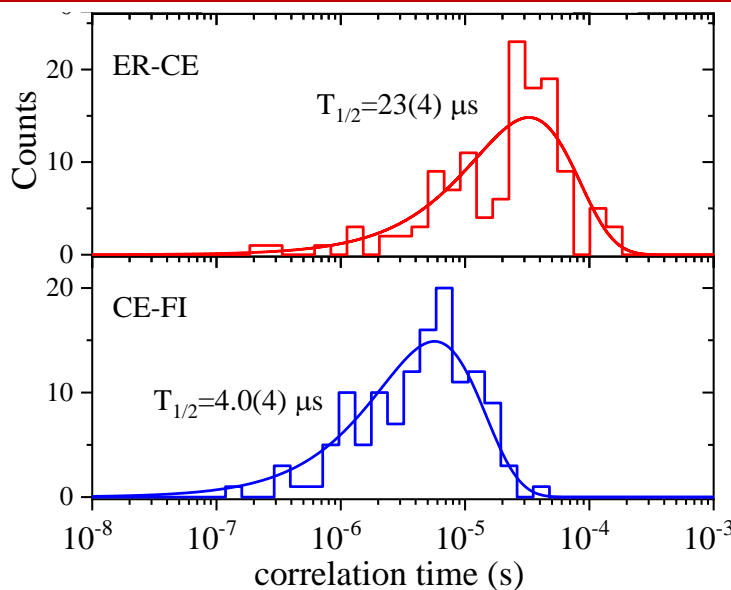
Search for direct fission from the long-lived  
K-isomeric state in  $^{250}\text{No}$

J. Khuyagbaatar et al., Phys. Rev. C **106**, 024309 (2022)


Low-energy and low-ionizing signal

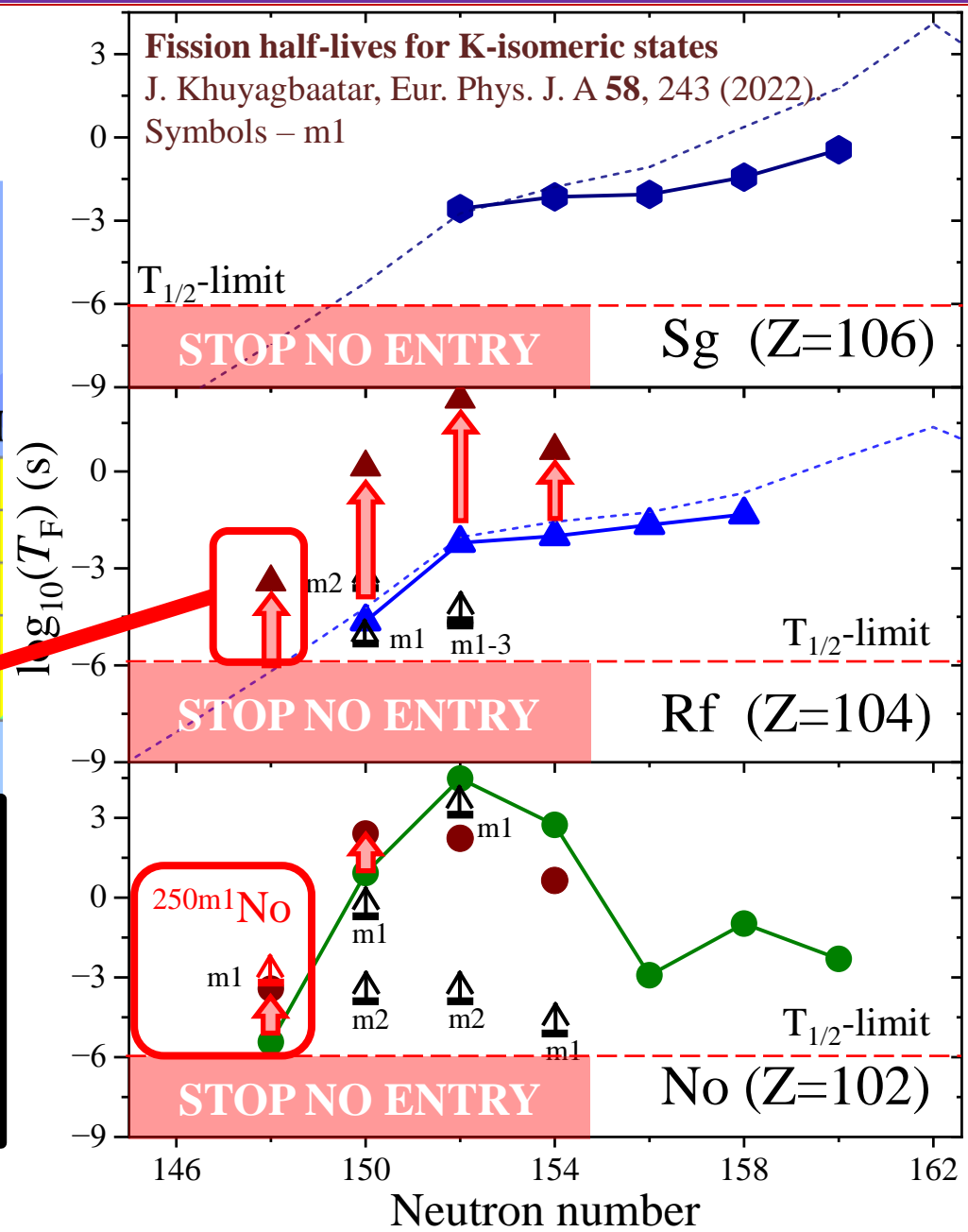
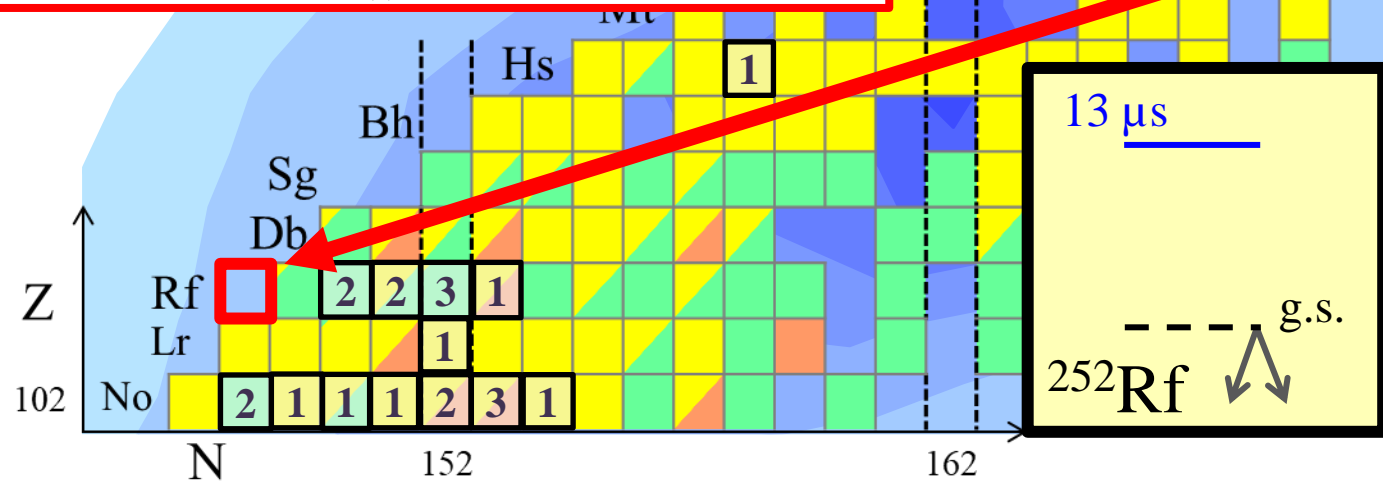
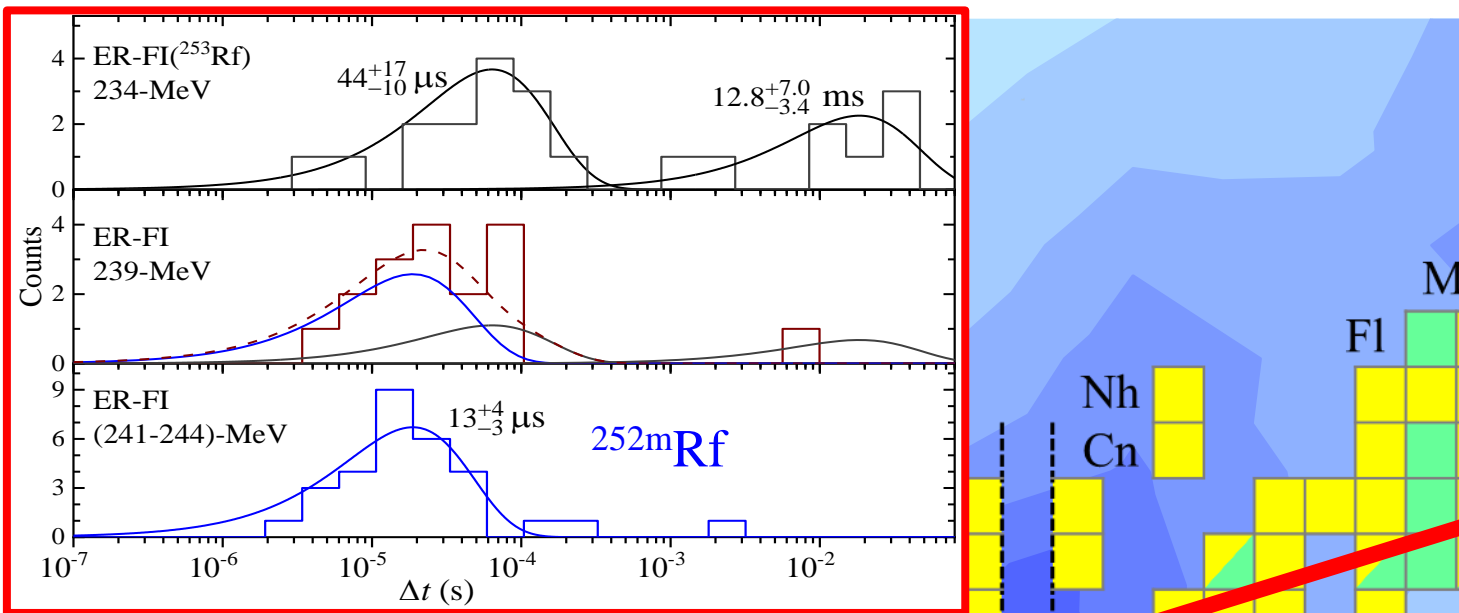
**Energy summing effect**

$$E(\text{CE}) = E_{\text{CE1}} + E_{\text{CE2}} + \dots \quad KE_{\text{FF1}} + KE_{\text{FF2}}$$

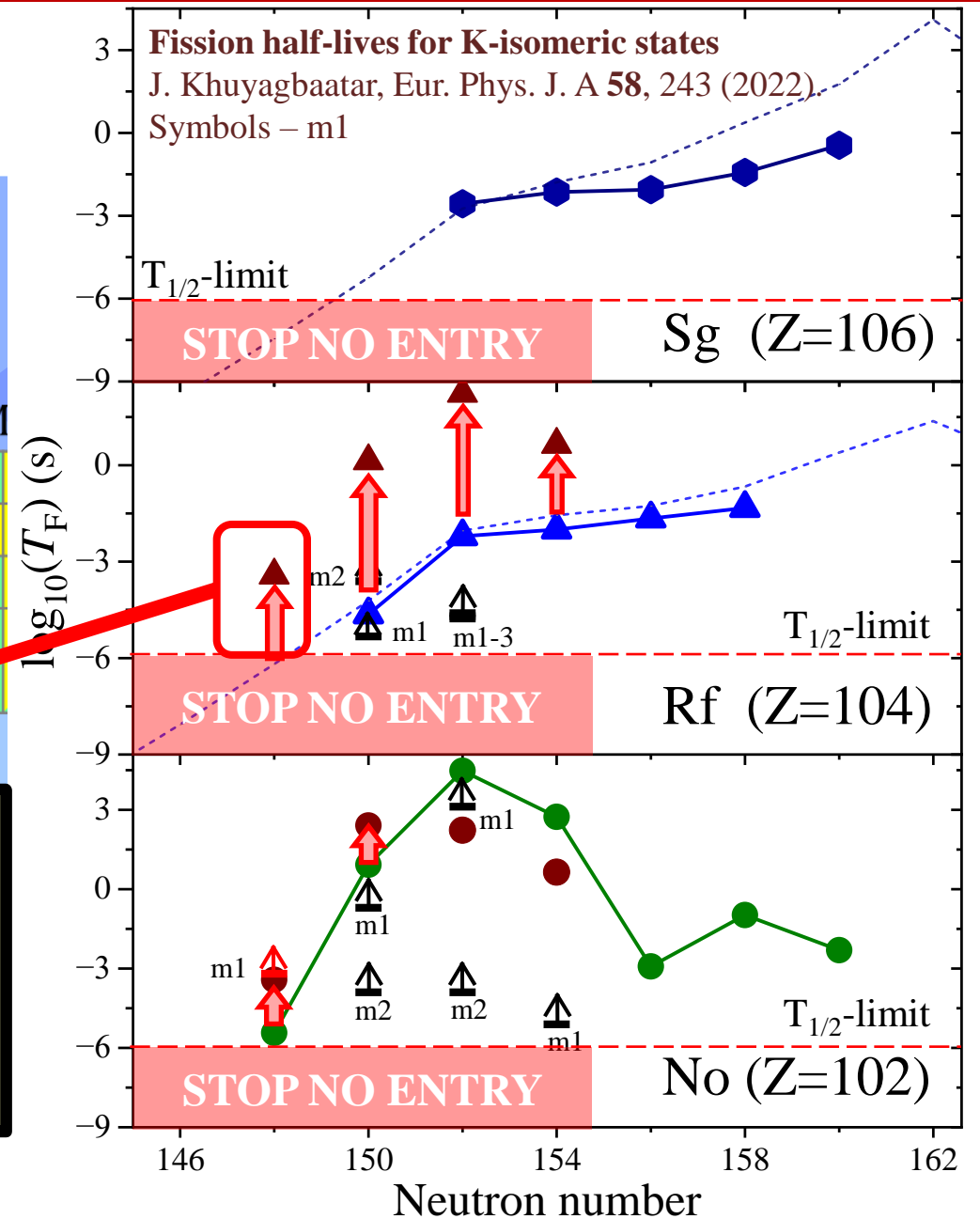
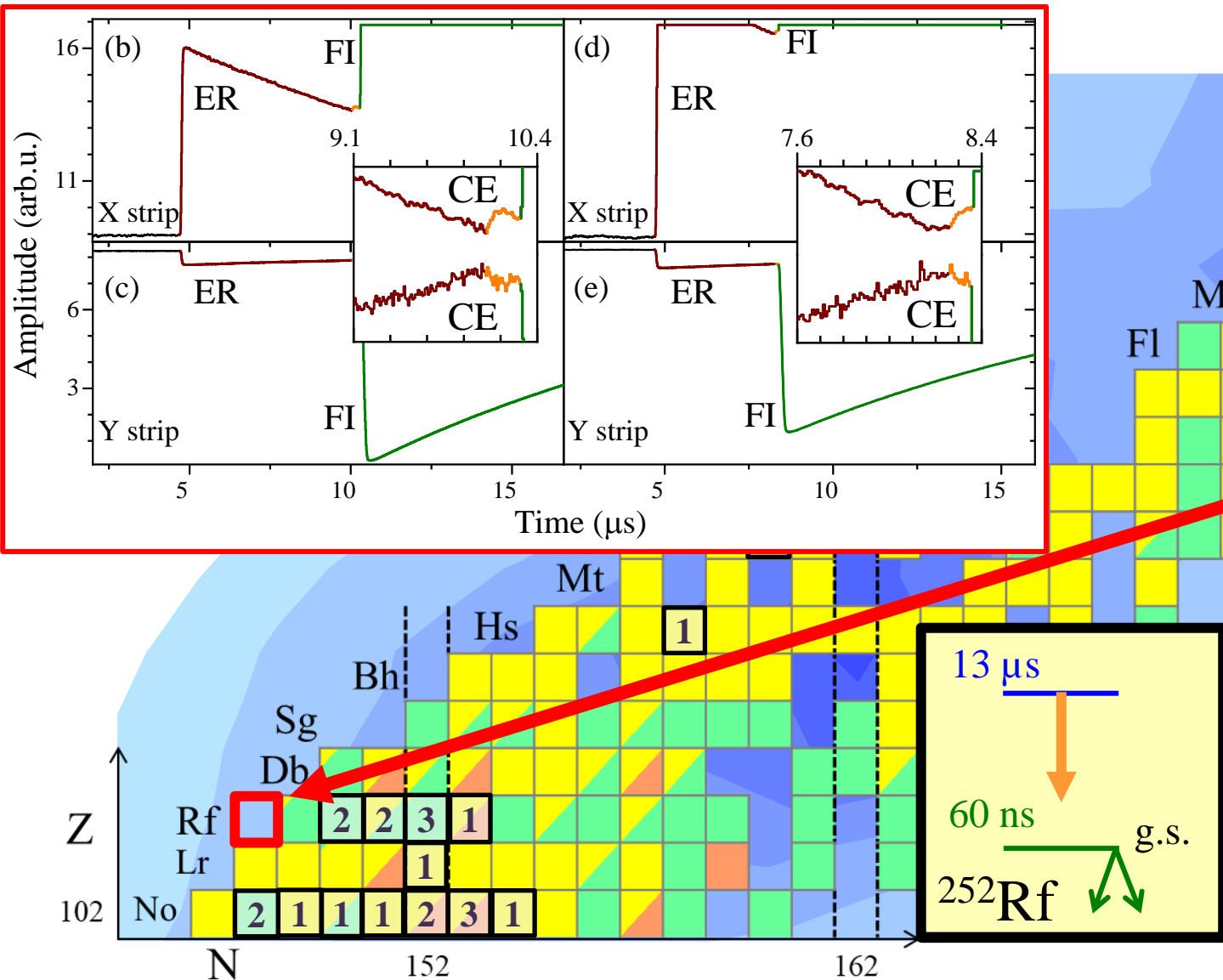


$^{50}\text{Ti} + ^{204}\text{Pb} \rightarrow ^{252}\text{Rf} + 2n$  @ **TASCA**

## ER-Fission correlation



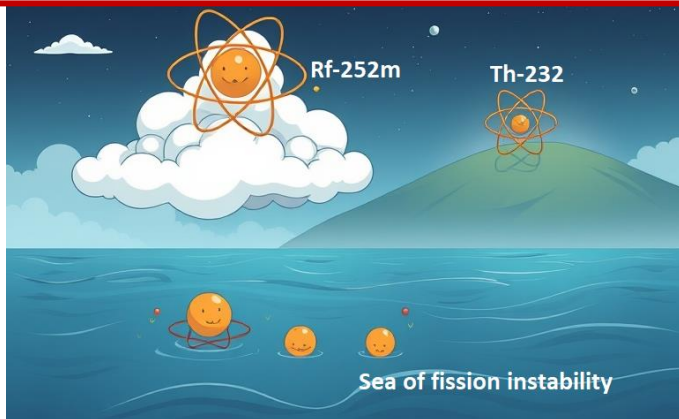
$^{50}\text{Ti} + ^{204}\text{Pb} \rightarrow ^{252}\text{Rf} + 2n$  @ **TASCA** Three **ER-CE-FI** events



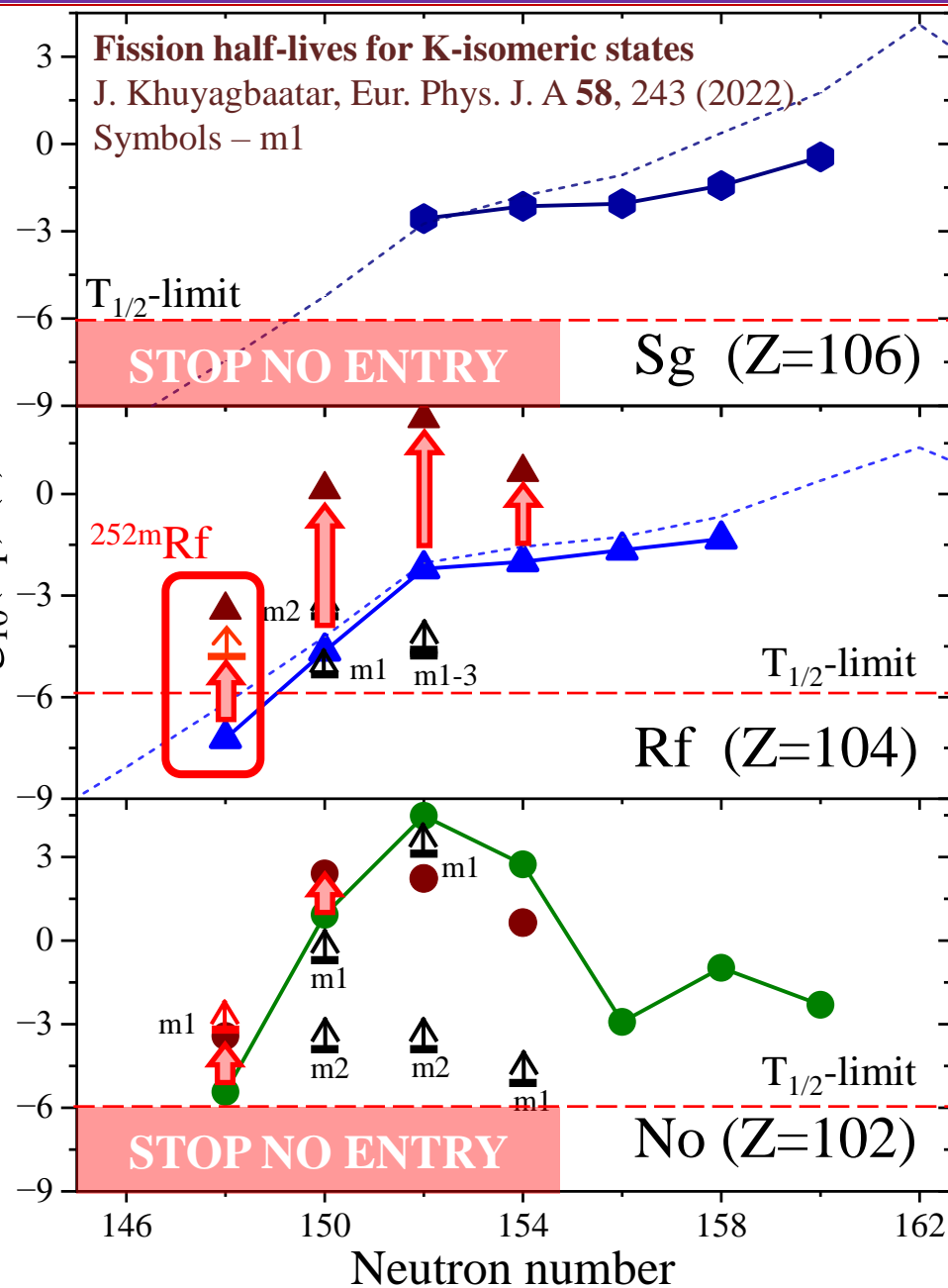
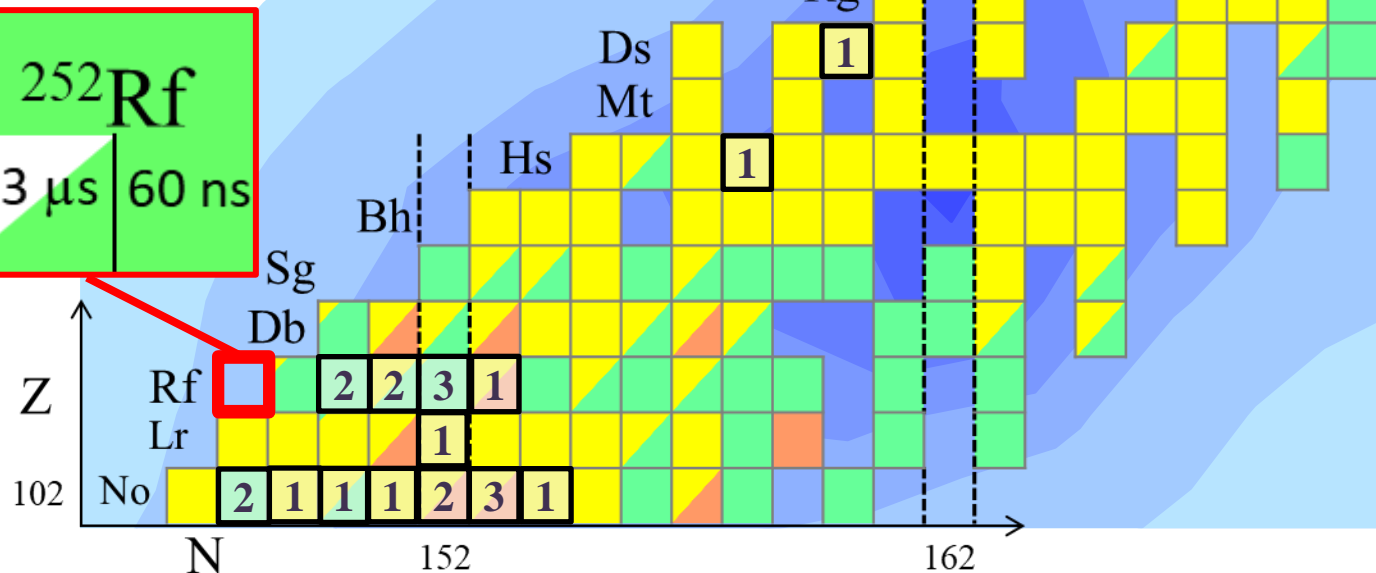
J. Khuyagbaatar, P. Mosat et al., Phys. Rev. Lett. **134**, 022501 (2025)

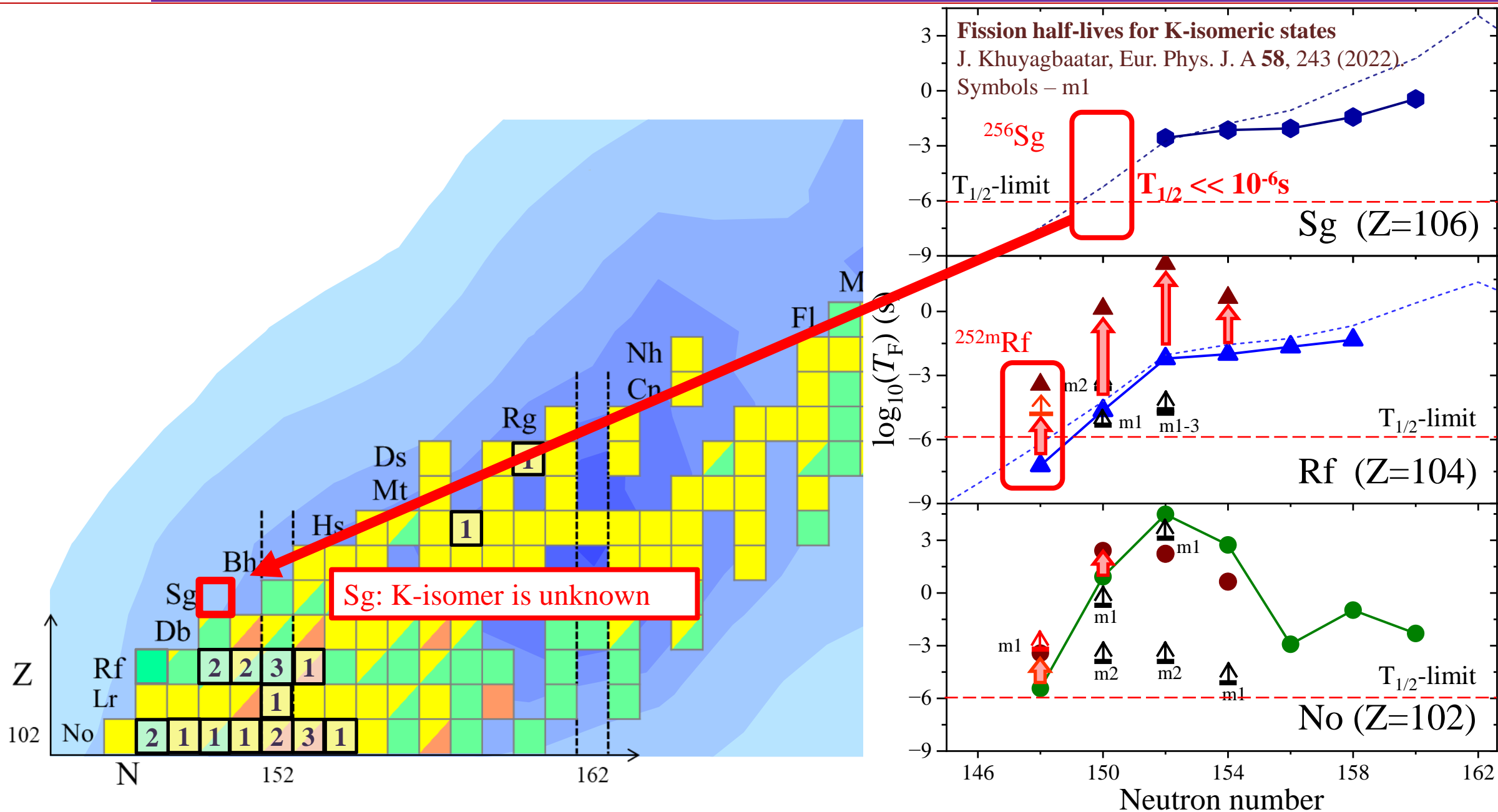
*Editors' Suggestion / Featured in Physics*

**Land ahoy! – Experiments at GSI/FAIR reveal the shoreline of the island of stability of superheavy elements (GSI press release)**



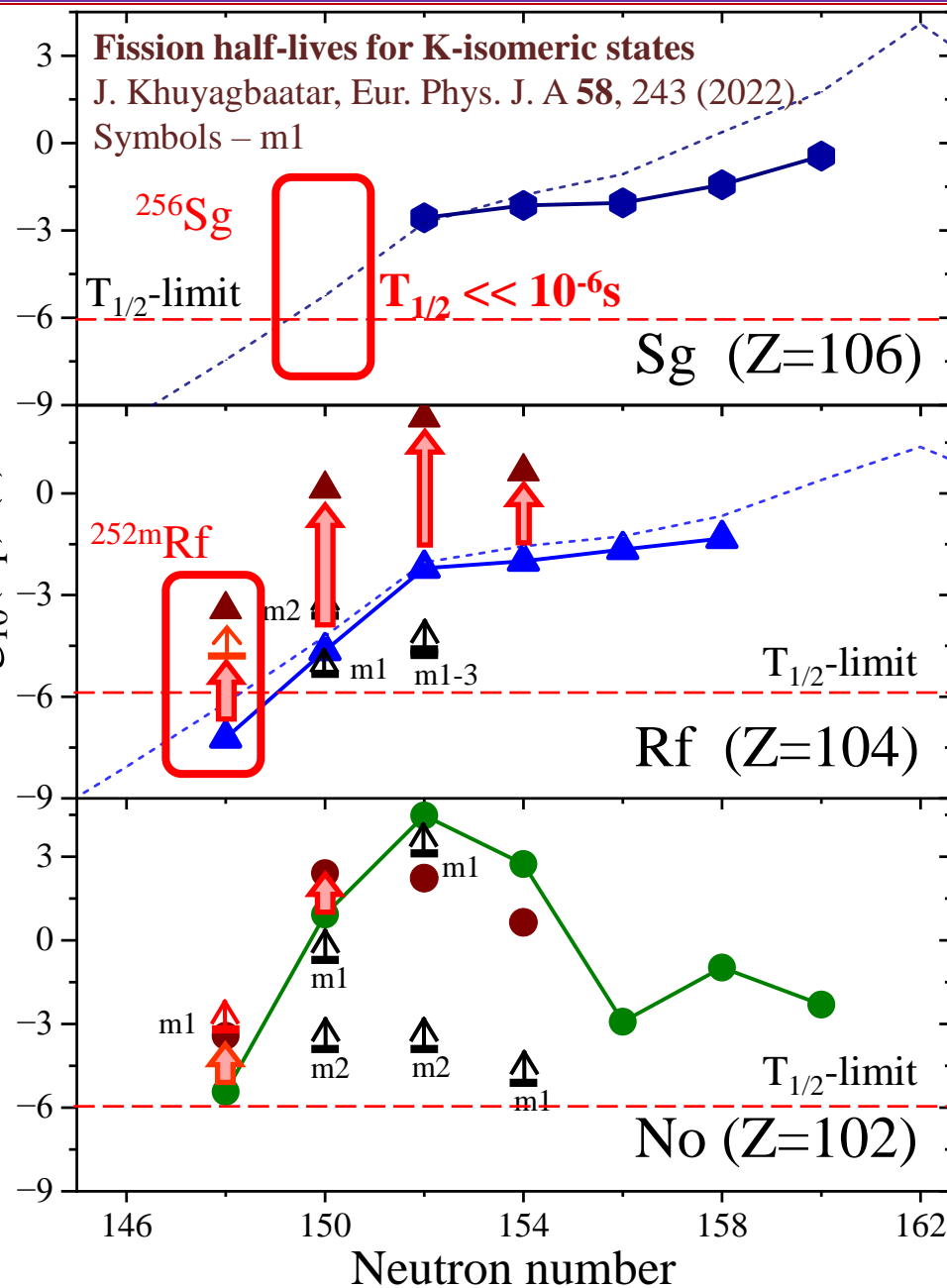
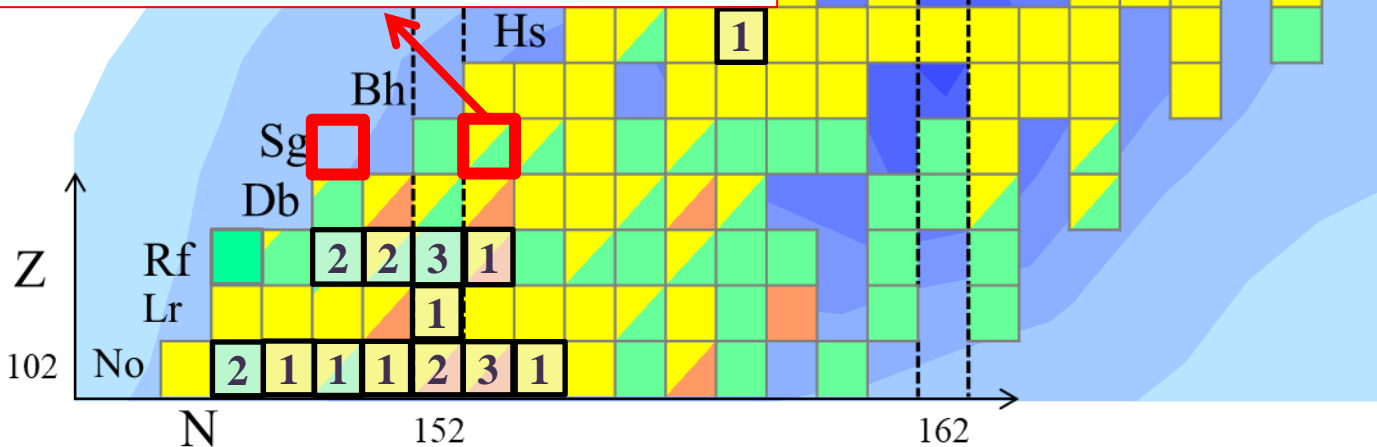
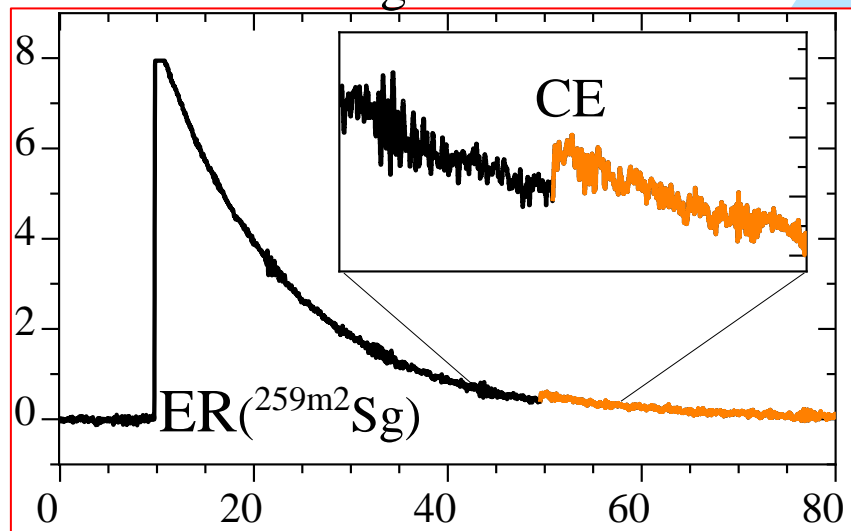
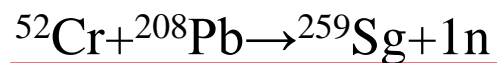
**$^{252}\text{Rf}$**   
13  $\mu\text{s}$  60 ns





P. Mosat, J. Khuyagbaatar, et al.,  
 Phys. Rev. Lett. **134**, 232501 (2025)

*Editors' Suggestion*

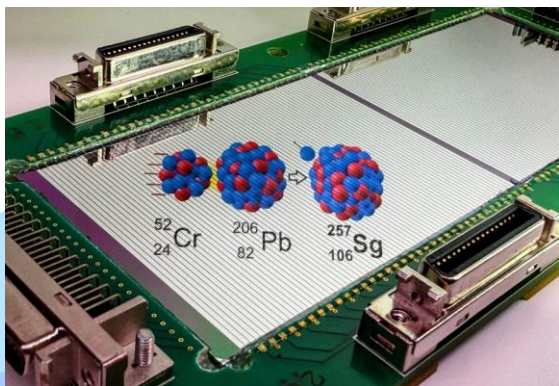


P. Mosat, J. Khuyagbaatar, et al.,  
 Phys. Rev. Lett. **134**, 232501 (2025)

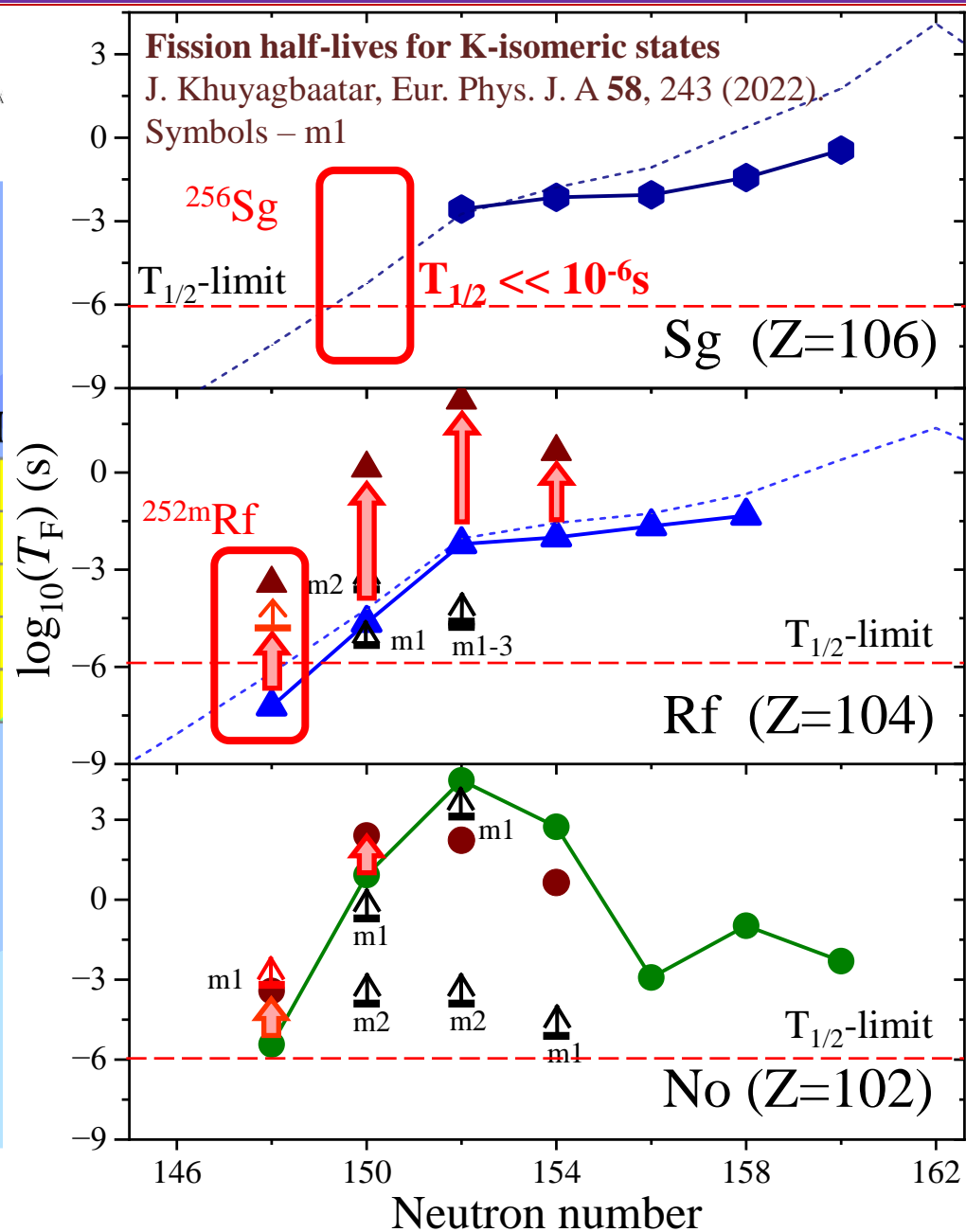
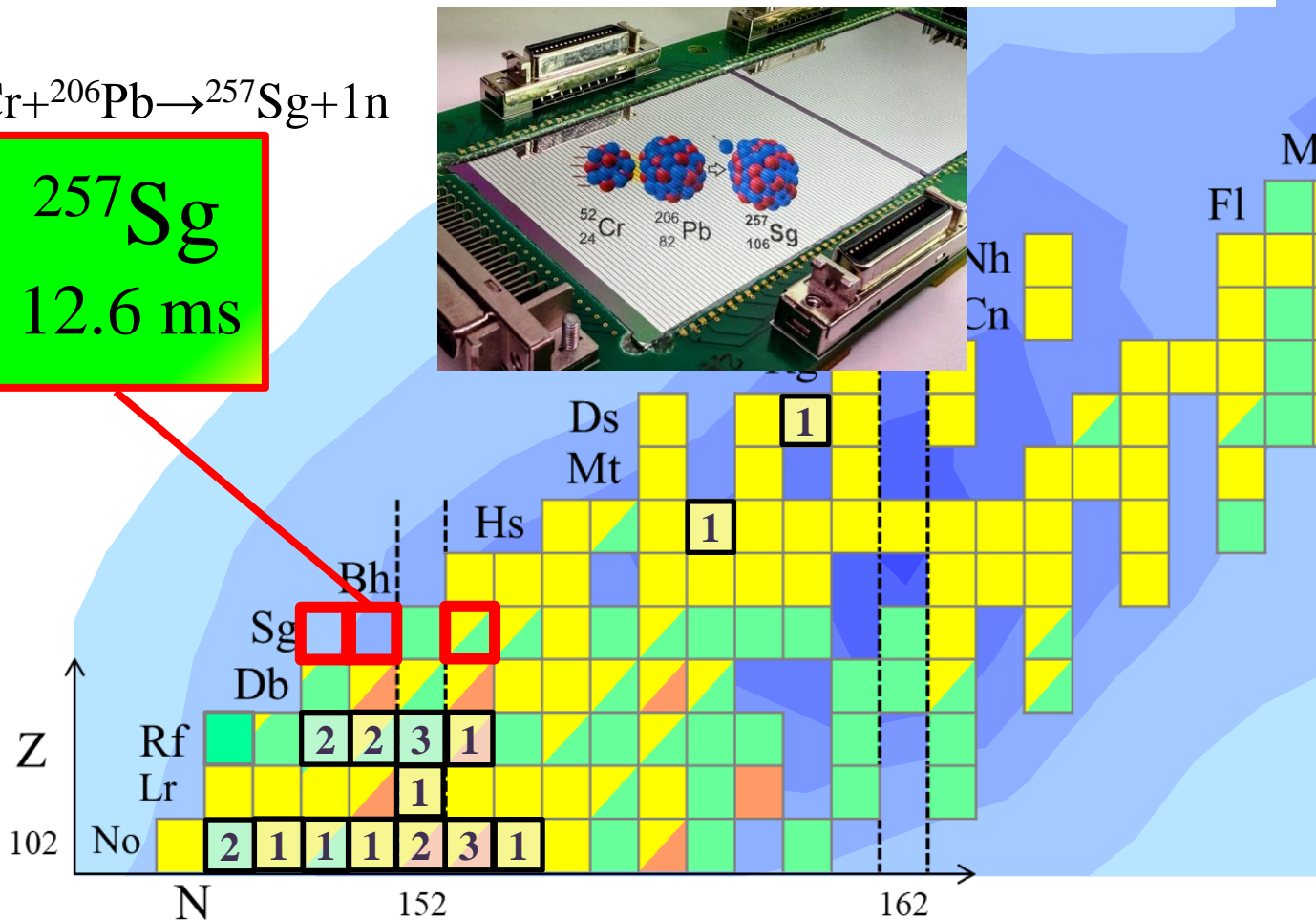


*Editors' Suggestion*

Expanding the border of superheavy nuclei — New seaborgium isotope discovered at GSI/FAIR (GSI press release)



$^{257}\text{Sg}$   
 12.6 ms



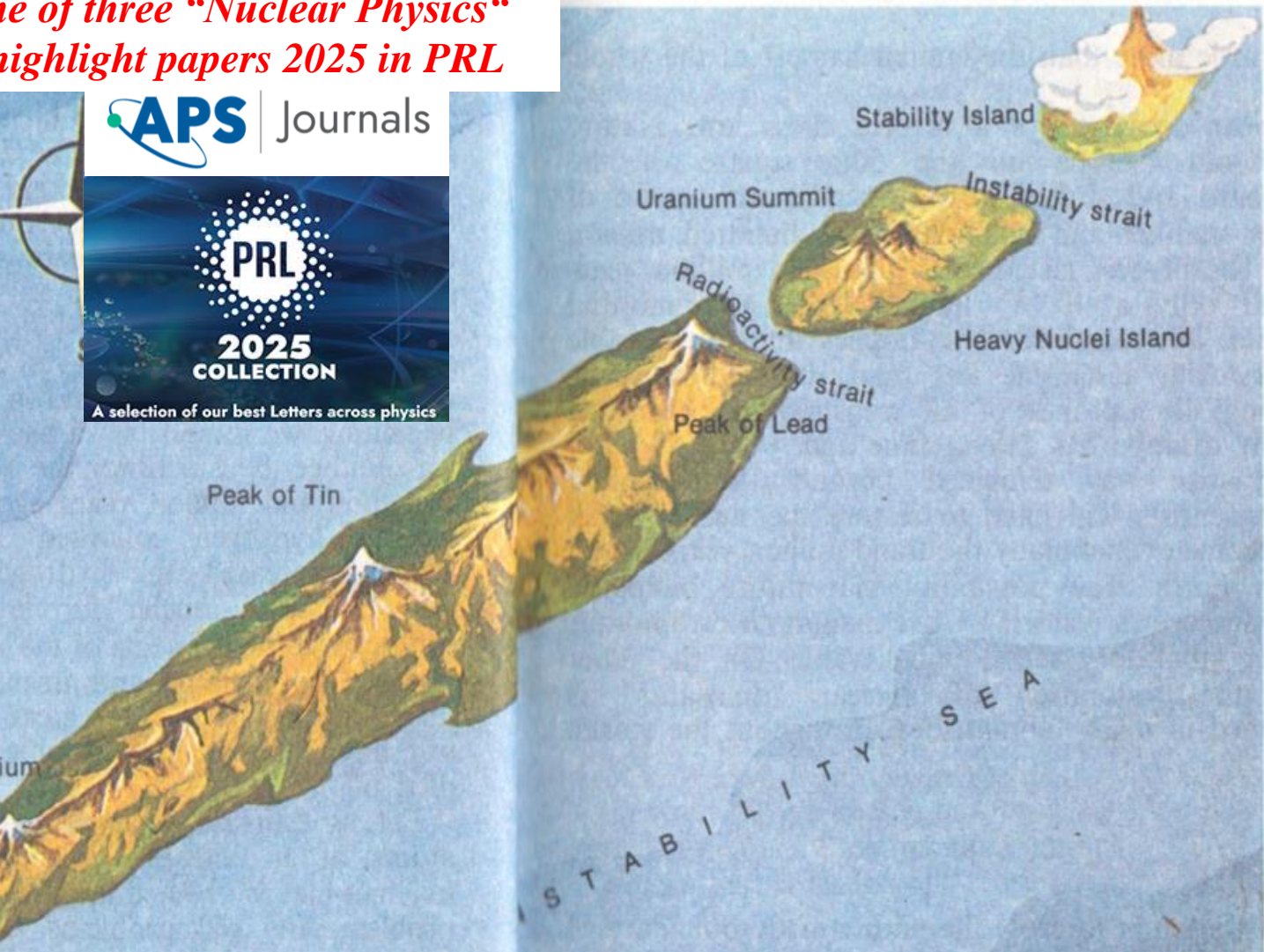
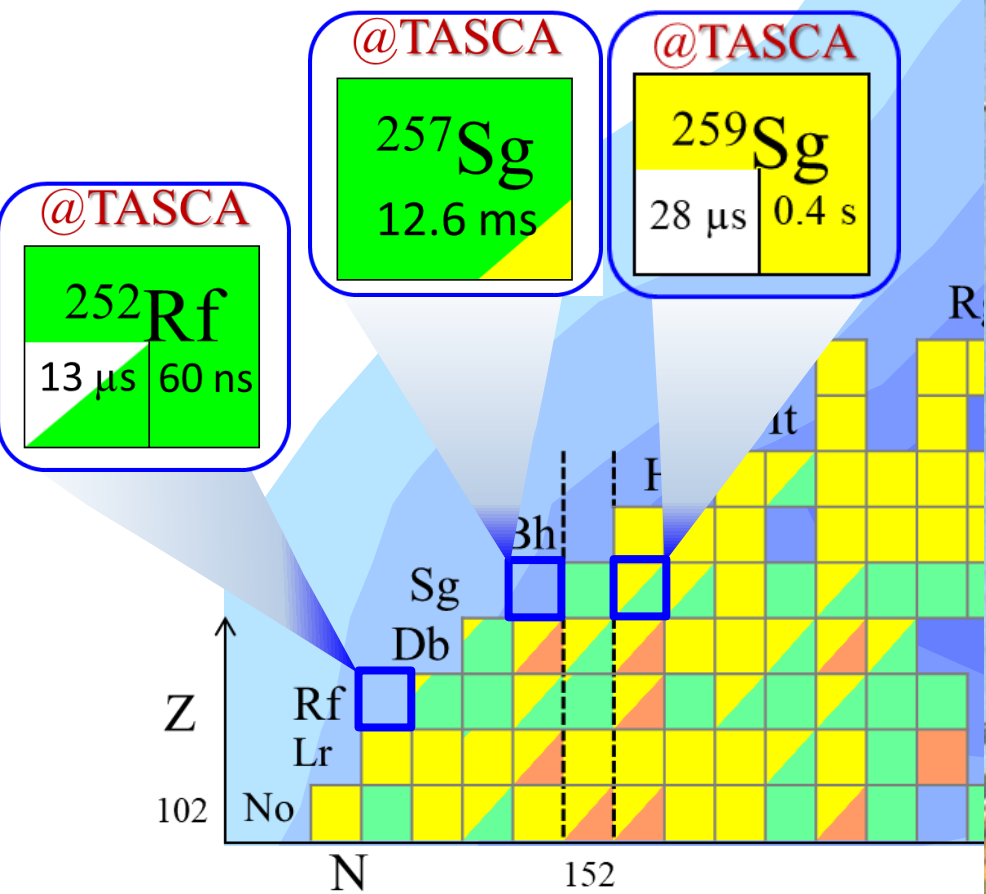
J. Khuyagbaatar, P. Mosat et al., Phys. Rev. Lett. **134**, 022501 (2025)

*Editors' Suggestion / Featured in Physics*

P. Mosat, J. Khuyagbaatar, et al., Phys. Rev. Lett. **134**, 232501 (2025)

*Editors' Suggestion / One of three "Nuclear Physics" highlight papers 2025 in PRL*

**Sea of instability**  
**K-isomer (clouds of stability)**



Properties of heavy and superheavy elements/nuclei are still hot topics in the field

Semi-empirical approaches for extracting the fission-barrier shape were developed

The SHN have narrow fission barrier

The K-isomers in SHN are very unique (clouds of stability) and should further be explored

Intensive scientific program at exploring the properties of SHN @ **TASCA** is still ongoing.

Discovery of second K-isomeric state in  $^{250}\text{No}$

Discoveries of the new sub- $\mu\text{s}$  isotope  $^{252}\text{Rf}$  and K-isomer

Discoveries of the new isotope  $^{257}\text{Sg}$  and K-isomer in  $^{259}\text{Sg}$



Thank you for your kind attention